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PROGRESSIVE METAMORPHISM OF SILICEOUS LIMESTONE AND DOLOMITE

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ABSTRACT

The metamorphism of siliceous dolomitic limestone is considered with the aid of a composition tetrahedron which suggests that the changes may be referred to thirteen steps or grades of increasing decarbonation, taking place at successively higher temperatures at any given pressure. At the temperature appropriate to each step a certain phase assemblage becomes unstable and each step is characterized by the disappearance of its appropriate phase assemblage. The survival of that phase assemblage in a rock is rigorously indicative of the fact that the step in question has not been attained.

In most of the steps, to wit ten, the *disappearance* of its phase assemblage is accompanied by a more conspicuous phenomenon, the *appearance* of a new phase, a metamorphic mineral, but this appearance of a new phase cannot be regarded as rigorously indicative of the accomplishment of the step since the new phase can be produced otherwise. Nevertheless, if certain additional conditions are fulfilled, the new phase will appear only when the temperature of the appropriate step is attained and the metamorphic minerals then become indicators of grade of metamorphism. In the order of the rising temperature steps at which they are produced the ten minerals are tremolite, forsterite, diopside, periclase, wollastonite, monticellite, akermanite, spurrite, merwinite, and larnite. Examination of their natural occurrence suggests that they are for the most part produced under conditions which permit their use as temperature indicators.

INTRODUCTION

Under certain conditions quartz and calcite crystallize side by side and appear to constitute a stable assemblage, but, when the temperature is raised, these minerals react with each other to form wollastonite and carbon dioxide. If there is indeed an equilibrium reaction, the temperature at which the reaction proceeds must depend upon the external pressure (pressure of CO_2). Goldschmidt was the first to point out the thermodynamic relations of this reaction

and its importance as an indicator of pressure-temperature conditions during rock metamorphism.[1] All subsequent studies of metamorphic rocks tend to confirm the view that the reaction represents a reversible equilibrium, although it has not proved possible to make a satisfactory laboratory study. Lime and silica form other compounds in addition to the metasilicate, and of these the orthosilicate is the most important from the present point of view, since it is the only one that has been identified in rocks. Niggli in 1916 studied experimentally the equilibrium in alkali carbonate melts containing SiO_2 and CaO, and concluded that the calcite-orthosilicate assemblage represents a higher temperature equilibrium at any given pressure than either the calcite-quartz assemblage or the calcite-wollastonite assemblage.[2] The application of these relations to rock metamorphism was not then apparent since calcium orthosilicate was not known in rocks. With its discovery by Tilley at Scawt Hill came indications of the applicability of Niggli's results to rock metamorphism, for the unusually high-temperature character of the Scawt Hill metamorphism was suggested by Tilley.[3]

There has been, then, some recognition of degrees of metamorphism of siliceous limestone, depending upon temperature; and, when we turn to the more complex case of siliceous dolomite, we find a like situation. The earliest developments of such concepts need not concern us. It will suffice to recall Eskola's establishment of four grades of metamorphism of siliceous (or silicified) magnesian limestone in western Massachusetts. These are represented, respectively, by quartz-limestone, tremolite limestone, diopside limestone. and wollastonite limestone in an ascending temperature series.[4] In addition, it is recognized by Niggli,[5] Tilley,[6] and others that monti-

[1] V. M. Goldschmidt, "Die Gesetze der Gesteinsmetamorphose," *Vid.-Selsk. Skr. I Math.-Naturv. Kl.* (1912), No. 22.

[2] P. Niggli, *Zeits. f. anorg. Chemie*, Vol. XCVIII (1916), p. 305.

[3] C. E. Tilley, *Min. Mag.*, Vol. XXII (1929), p. 86.

[4] Pentti Eskola, "On Contact Phenomena between Gneiss and Limestone in Western Massachusetts," *Jour. Geol.*, Vol. XXX (1922), p. 283.

[5] U. Grubenmann and P. Niggli, *Die Gesteinsmetamorphose*, Vol. I (Berlin: Gebrüder Borntraeger, 1924), p. 383.

[6] "Contact Metamorphic Assemblages in the System, CaO-MgO-Al_2O_3-SiO_2," *Geol. Mag.*, Vol. LXII (1925), p. 366.

cellite assemblages represent a higher grade of metamorphism of magnesian limestone than any of the assemblages discussed by Eskola in connection with his Massachusetts studies. But in spite of this general knowledge of grades of metamorphism of the rocks under consideration and very detailed treatment of some aspects of it, such as that by Goldschmidt, there appears to be no examination of the whole subject with adequate emphasis upon the progressive character of the metamorphism, in other words, upon degree or grade of metamorphism. The present paper is an attempt to supply the need of such systematic treatment.[7] Some aspects of the discussion will undoubtedly require revision in the light of better knowledge. In so far as they have been apprehended, questionable points have been noted and in part debated at the appropriate places.

PROGRESSIVE METAMORPHISM OF SILICEOUS LIMESTONE

The reaction between calcite and quartz to form wollastonite may be represented by the equation

$$CaCO_3 + SiO_2 \rightleftharpoons CaSiO_3 + CO_2 , \qquad (A)$$

[7] This material was first brought together with the purpose of presenting to students as a logical whole, with a connecting thread of fundamental law, a subject that otherwise is bare, arid description. When this had been done, it was thought that the paper had enough novel aspects to warrant its presentation at the Minneapolis meeting of the Geological Society of America. Upon hearing the paper, Professor A. F. Buddington called my attention to a contribution by Korjinski to the International Geological Congress in Moscow and has since sent me a printed extract (D. S. Korjinski, *Mem. Soc. Russe de Min.*, Vol. XLVI [1937], p. 385). Korjinski there treats briefly the general subject of the stability range of minerals, emphasizing the control of depth (pressure). One aspect of his problem is concerned with the decomposition of silicates by CO_2 at various pressures, which is substantially the reverse of our present problem. Referring especially to lime-alumina silicates, he invokes some of the same principles and adopts a method of approach which, in some respects, resembles that adopted in the present paper. Korjinski's extract is so brief that one may do him an injustice in offering criticism based on it, but he appears to assume that there is always an unlimited supply of CO_2 in the depths and thus reaches conclusions as to the existence of certain silicates in the depths which are at variance with the facts. In any case, the problem of progressive metamorphism of carbonates cannot be regarded as the simple inverse of his problem and is more profitably attacked in the general manner that is followed in the present paper.

and inspection of this equation shows that we have to deal with a three-component system because three is the least number of substances in terms of which the composition of all four of the phases can be expressed. A system of three components existing in four phases has one degree of freedom, as the ordinary equation of the phase rule $P + F = C + 2$ shows.[8] With only one degree of freedom the fixing of any one variable fixes all others, so that if the pressure is fixed the temperature is also fixed. In other words, these four phases can coexist in equilibrium with one another at only one temperature if the pressure (of CO_2) is given. Therefore a pressure-temperature curve can be drawn showing for each pressure (of CO_2) the temperature at which all four phases are in equilibrium. Such a curve is shown in Figure A and is known as a curve of univariant equilibrium (one degree of freedom). For all values of the temperature and pressure which do not lie on this curve, not more than three phases can coexist in equilibrium, and the curve of univariant equilibrium thus separates two areas of divariant equilibrium. We may readily decide which phases can exist in each of these fields by turning to the equation for the reaction. Quartz and calcite represent the low-temperature pair at any pressure; wollastonite and CO_2, the high-temperature pair. But in association with calcite and quartz either wollastonite or CO_2 (but not both) can occur on the low-temperature side, and in association with wollastonite and CO_2 either calcite or quartz (but not both) can occur on the high-temperature side. In

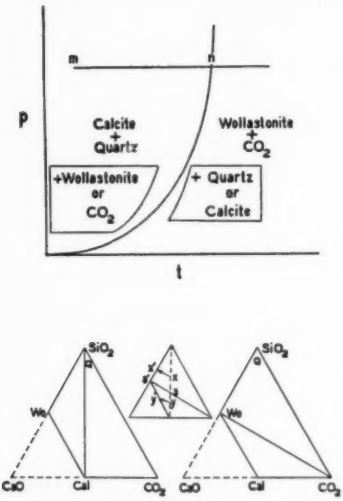

FIG. A.—Pressure-temperature diagram and paired composition diagrams of reaction equation *A*.

[8] In this equation P = the number of phases in a system at equilibrium, C = the number of components, and F = the number of degrees of freedom.

other words, we have as possible three-phase assemblages all possible combinations of the four phases taken three at a time, which gives four three-phase assemblages, two of which are low-temperature assemblages and two are high-temperature assemblages, thus:

a) calcite + quartz + wollastonite *b*) calcite + quartz + CO_2	low temperature
c) wollastonite + CO_2 + quartz *d*) wollastonite + CO_2 + calcite	high temperature

These relations are shown on the diagram (Fig. A), the low-temperature assemblages being placed on the low-temperature side of the univariant curve and the high-temperature assemblages on the high-temperature side. The diagram may now be put to service in attacking the problem of metamorphism of siliceous limestone (or calcareous quartzite), as Goldschmidt did long ago. We need concern ourselves only with the case where calcite and quartz alone are present in the rock, which exists at a pressure and temperature indicated by the point *m* on the diagram, that is, a low temperature and a rather high pressure. If now the temperature is raised, the applied pressure will remain unchanged at the initial value and no new phases will form, the change of condition being given by the horizontal line *mn*, which indicates only a rise of temperature at constant pressure. But when the temperature has risen to *n*, the vapor pressure of the reacting system has now reached a value equal to the external pressure, and some vapor (CO_2) will form and with it some wollastonite. At the fixed external pressure the four phases can coexist at only one temperature, and the temperature will therefore remain constant at *n* until one phase of the low-temperature assemblage, calcite or quartz, disappears. Only when the reaction is complete can the temperature rise above *n*, which will be represented by movement along *mn* produced, the pressure remaining at the fixed value of the external applied pressure. Ordinarily all or nearly all the vapor of CO_2 will escape from the system, and the product will then consist of wollastonite with either quartz or calcite in excess, according to their relative proportion in the original rock. It is especially noteworthy that, although we are dealing with a three-

component system, the product of metamorphism would consist of only two solid phases. For this special type of metamorphism, then, the number of *mineral* phases formed is one less than the number of components and not equal to the number of components as Goldschmidt has shown it must ordinarily be to satisfy divariance (random temperature and pressure). We have here one *mineral* phase less than usual because one phase on the high-temperature side is the gas CO_2 which is lost to the system.[9]

Certain aspects of the chemical relations in such a system are best pictured with the aid of a composition diagram which for this three-component system may be shown on triangular coordinates. Figure A shows two such diagrams in which CaO, CO_2, and SiO_2 are taken as components. The first triangular diagram of Figure A represents the low-temperature assemblages. In it all phases which can coexist at these temperatures are joined by straight lines. There is, therefore, a line joining SiO_2 and $CaCO_3$ and another joining $CaCO_3$ and wollastonite. The rest of the triangle toward the CaO corner has no significance in the present connection and is shown merely in dotted outline. The two triangles bounded by full lines on this first triangular diagram of Figure A bring out clearly the two low-temperature, three-phase assemblages, calcite + quartz + wollastonite and calcite + quartz + CO_2 which have already been mentioned. The diagram is thus perfectly general, in accordance with phase-rule requirements, but the really significant feature is that quartz and calcite can coexist in equilibrium under the low-temperature conditions to which this diagram applies. The quartz-calcite join is thus the line on this diagram of special significance and the only one of practical importance since the three-phase assemblages with either some wollastonite or some CO_2 are probably seldom represented in any natural rock. Nevertheless, to make the reasoning all inclusive, it is necessary to show these three-phase areas (triangles) in order that it

[9] When the composition is such that a quartz-wollastonite rock is the product of metamorphism, CO_2 is, of course, no longer a component of the system, and the number of components is reduced to two, which is the same as the number of phases, in correspondence with the usual case for which Goldschmidt has stated his Mineralogical Phase Rule.

may be realized that, if there were a limestone containing some detrital wollastonite and if it were recrystallized (metamorphosed) under these low-temperature conditions, quartz, calcite, and wollastonite could recrystallize side by side in perfect equilibrium with one another.

We may now suppose that a rise of temperature takes place under constant external pressure corresponding with movement along the line *mn* of the P-T diagram in Figure A, which we have already considered. When the temperature has reached the value *n*, calcite and quartz, we found, can no longer coexist; one of them must disappear. The phases which can now coexist are shown in the second large triangle of Figure A, in which again pairs of coexistent phases are joined by straight lines. The join calcite-quartz has disappeared and in its place appears the join wollastonite-CO_2 which crosses it. These are the four reacting phases of equation *A*, and it is a general relation for such a univariant reaction that in a composition diagram the line joining the two phases on one side of the equation must cross the line joining the two phases on the other side of the equation. The reacting phases are said to bear a "crossed relation." The small subsidiary triangle of Figure A enables us to picture more clearly what happens to mixtures of quartz and calcite (and indeed such mixtures with some wollastonite in addition) when they pass through the temperature *n* of the P-T diagram. Any mixture such as *x* which lies between *a* and SiO_2 on the dotted join $CaCO_3$-SiO_2 will, as a result of loss of CO_2, have its composition changed in a manner represented by the line *xx'*, which points directly away from the CO_2 corner of the triangle. The final product of metamorphism will be *x'*, a mixture of wollastonite and quartz. Any mixture such as *y*, lying between *a* and $CaCO_3$, will have its composition changed to *y'*, a mixture of wollastonite and calcite. The mixture *a* itself which contains calcite and quartz in chemical equivalents would, of course, be transformed into wollastonite alone (*a'*). It is clear, then, that the constitution of the metamorphic product can be determined with the aid of the two large triangular diagrams of Figure A simply by considering movement of the composition in a direction away from the CO_2 corner of the triangle until the first join of coexistent

phases for the new conditions is encountered. The two large triangular diagrams of Figure A may conveniently be called the paired diagrams of the reaction given in equation *A*.[10] We shall have occasion to use such paired diagrams a great deal and to refer to them as such. The paired diagrams and the considerations just brought out demonstrate that in such materials metamorphism is essentially *decarbonation*, and, as the discussion proceeds, it will become clear that progressive metamorphism is essentially progressive decarbonation.

At this point it is desirable to emphasize the central feature of this whole discussion of equilibrium in its application to actual rocks. The presence of calcite and quartz in a rock indicates that the temperature at which these become incompatible at the pressure then prevailing was not exceeded. On the other hand, the presence of wollastonite does not indicate that that temperature was exceeded, since wollastonite can, as we have seen, be present in one of the low-temperature, three-phase assemblages. Of course, if it were perfectly certain that the rock initially contained only quartz and calcite, the formation of some wollastonite would, with some qualification, indicate that the temperature in question had been exceeded. This will be discussed more fully at a later point, especially with reference to the qualification referred to.

We may now turn to a consideration of the next step in the progressive metamorphism (progressive decarbonation) of siliceous limestone. In the first step a reaction took place as a result of the fact that calcium carbonate was no longer stable in contact with pure SiO_2. In this next step (at a higher temperature for the same pressure) calcium carbonate becomes unstable in contact with calcium metasilicate (wollastonite) and reacts with it to produce spurrite and CO_2 in accordance with the equation

$$3CaCO_3 + 2CaSiO_3 \rightleftarrows 2Ca_2SiO_4 \cdot CaCO_3 + 2CO_2 . \qquad (B)$$

[10] Thus equation *A*, the univariant reaction (P-T) curve of Fig. A and the paired triangular diagrams of Fig. A all express the same facts, each with its own emphasis. This system of referring to the equation, the figure, and the P-T curve of any reaction by the same letter or number will be followed throughout the paper.

As before we have four three-phase assemblages, thus:

a) calcite + wollastonite + spurrite } low temperature
b) calcite + wollastonite + CO_2 }

c) spurrite + CO_2 + calcite } high temperature
d) spurrite + CO_2 + wollastonite }

Again there are paired diagrams which show these stable phase assemblages at lower temperatures and at higher temperatures, respectively. The lower-temperature diagram of this pair is the same as the higher-temperature one of the previous pair (Fig. A) which illustrated the preceding step of metamorphism. The new pair is given in Figure B. The join calcite-wollastonite of the first diagram of Figure B disappears in the second diagram of that figure where it is replaced by the join spurrite-CO_2, and these two joins have as before the crossed relation. Compositions which originally lay on the join calcite-wollastonite are moved over, as a result of loss of CO_2, to their appropriate points on the join spurrite-wollastonite or the join spurrite-calcite, the construction for which is readily obtained by drawing lines directly away from the CO_2 corner in a manner already discussed for the previous step. Here, as before, the coexistence of calcite and wollastonite in a rock indicates a low temperature (in relation to this reaction), but only with some qualification can the presence of spurrite be regarded as indicating a high temperature.

A final step in the progressive metamorphism of siliceous limestone comes if the temperature is raised to the still higher value (at the same pressure) at which wollastonite and spurrite react to give larnite and CO_2 according to the equation

$$CaSiO_3 + 2Ca_2SiO_4 \cdot CaCO_3 \rightleftharpoons 3Ca_2SiO_4 + CO_2 . \qquad (C)$$

The four three-phase assemblages are:

a) wollastonite + spurrite + larnite } lower temperatures
b) wollastonite + spurrite + CO_2 }

c) larnite + CO_2 + wollastonite } higher temperatures
d) larnite + CO_2 + spurrite }

The paired diagrams for this reaction, showing the stable-phase assemblages below and above the reaction temperature, are shown in Figure C. The join wollastonite-spurrite disappears and is replaced by the join larnite-CO_2 which has the crossed relation to it. Again the change of composition involved can be pictured by a movement directly away from the CO_2 corner of the triangle whereby compositions represented by points on the wollastonite-spurrite join will move to points either on the spurrite-larnite join or on the larnite-wollastonite join.

Further comment is necessary on this step in metamorphism as here depicted. It makes larnite and wollastonite capable of co-

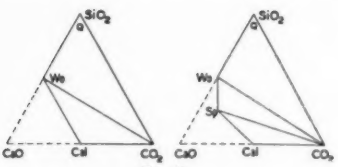

FIG. B

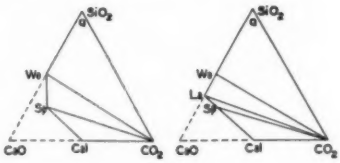

FIG. C

FIG. B.—Paired composition diagrams of reaction equation *B*

FIG. C.—Paired composition diagrams of reaction equation *C*

existence. Experimental studies show that Ca_2SiO_4 and $CaSiO_3$ do not occur together at high temperatures but combine to form the compound $3CaO \cdot 2SiO_2$. The 3:2 compound has, however, never been found in nature, and, in the metamorphic haloes around chalk nodules at Scawt Hill, larnite and wollastonite zones come together without any interposition. Perhaps the 3:2 compound has a minimum temperature of existence which is higher than any of the temperatures of metamorphism.

With advance of knowledge the above discussion of three steps in the progressive metamorphism of limestone may require revision, but it appears to represent present knowledge and may serve to emphasize principles. At any given pressure calcite and quartz can coexist in equilibrium only up to a certain temperature, calcite and wollastonite can coexist up to a somewhat higher temperature, spurrite and wollastonite up to a still higher temperature, and above this none of these pairs can exist. Each of these pairs is thus an indicator

of the degree or grade of metamorphism or temperature of metamorphism at a given pressure. Each step in metamorphism is a successive step in decarbonation. If a triangular diagram is drawn with CaO, SiO_2, and CO_2 at its corners and calcite is joined by a line to each of the phases with which it can coexist, then the successive steps in decarbonation (i.e., the successive steps in metamorphism) can be deduced entirely from geometrical relations in the triangle by observing the joins successively encountered with motion away from the CO_2 corner, i.e., decarbonation. We shall now proceed to apply this concept to the more complex case of the metamorphism of siliceous magnesian limestone.

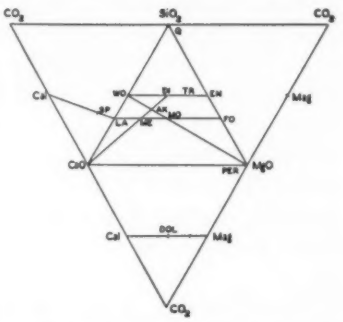

FIG. D.—Skeleton diagram of tetrahedron, illustrating composition of phases in metamorphosed, siliceous, dolomitic limestone.

PROGRESSIVE METAMORPHISM OF SILICEOUS DOLOMITE

For the purpose of studying the metamorphism of siliceous dolomite or dolomitic limestone it is convenient to use a tetrahedron which has as the base the CaO-MgO-SiO_2 triangle and CO_2 as its apex, the tetrahedron that would be formed from Figure D if the three outer triangles were folded up until their three CO_2 apices met at a common point—the CO_2 apex of the tetrahedron. On the base should be plotted the points representing the compositions of all the Ca-Mg silicate compounds known to form in metamorphosed carbonate rocks of the kinds here under consideration,[11] and in their appropriate places the points for spurrite, dolomite, and calcite. By considering the relative positions in this tetrahedron of the various planes that are formed by joining calcite and dolomite (or MgO) to the various silicate phases on the base, the steps in the metamorphism (decarbonation) of siliceous carbonate rocks in their correct order can be deduced partly from geometrical relations, though

[11] Magnesite or any carbonate richer in magnesia than dolomite will not be considered.

these must be supplemented by knowledge of possible silicate assemblages.

In our consideration of the metamorphism of siliceous limestone we found that two mineral phases and CO_2 were formed at each step and that lines radiating from the CO_2 corner of the composition triangle encounter successively the lines joining the pairs of minerals formed in each successive step. In the present case we have one more component; therefore, three mineral phases and CO_2 are ordinarily formed at each step in metamorphism, and lines radiating from the CO_2 apex of the tetrahedron will, in the same manner, encounter successively the planes (triangles) formed by joining the compositions of the three mineral phases formed at each successive step of metamorphism (decarbonation). It serves no useful purpose to make a drawing of the composition tetrahedron showing these planes. Their relative position can be visualized readily only with the aid of a model.[12] We can, however, with the tetrahedral model ever before us as an aid, draw a series of diagrams which show the planes successively encountered and therefore the phases formed in various compositions at successive steps in metamorphism. These diagrams represent certain triangular planes within the tetrahedron and are best shown as projected upon the base of the tetrahedron, with the CO_2 apex as the center of projection, so that each diagram becomes an equilateral triangle, the point for $CaCO_3$ coinciding with the CaO point, the point for $MgCO_3$ coinciding with the MgO point, and the point for dolomite lying halfway between these.

The highest (closest to the CO_2 apex) of the series of planes within the tetrahedron is that representing no decarbonation and is the plane determined by the points calcite, dolomite, and SiO_2. This is shown in the first diagram of Figure 1. It indicates that at low temperatures calcite, dolomite, and quartz can coexist in equilibrium,

[12] Students who became interested in this problem constructed tetrahedra to aid in its solution. One device adopted proved particularly simple and effective. It consisted in making up a cardboard tetrahedron with one face lacking. This missing face is taken as the MgO-CO_2-SiO_2 face, with which compositions we are not here concerned. The absence of this face renders accessible the whole interior of the tetrahedron so that the compositions of the phases can be plotted on the interior side of the other faces and colored threads can be strung from point to point. These lines (threads) determine the planes encountered in the decarbonation of any composition within the tetrahedron. Among the more active students may be mentioned H. Stocking and F. E. Tippie.

and with metamorphism at the lowest temperatures they can recrystallize side by side. At a higher temperature, however, they react, and, depending upon the temperature (at a given pressure) a series of products may result. If the temperature is raised only a moderate amount, the product is a tremolite-bearing rock. It is an unfortunate feature of the metamorphism of siliceous dolomite that the very first step exhibits unusual features which make it impossible to represent it rigorously with the aid of the tetrahedron we have been considering. Tremolite contains water as an essential constituent, and its composition cannot therefore be represented in this tetrahedron. In order to plot tremolite, it has been necessary to neglect its water content, and in the plots the composition $CaMg_3(SiO_3)_4$, often given in old texts, is used as the tremolite point. When this is done, triangular planes with tremolite at a corner are the first planes encountered in the tetrahedron in moving from points in the calcite-dolomite-silica plane in a direction directly away from the CO_2 apex (decarbonation). The tetrahedron, even with this simplification of the composition of tremolite, thus accurately represents the first product of metamorphism of siliceous dolomite (or dolomitic lime), which is well known to be tremolite. The planes encountered are two in number: the tremolite-quartz-calcite plane and the tremolite-dolomite-calcite plane. In the tetrahedron they are not co-planar, but, when projected in the manner described above, they appear as shown in the second diagram of Figure 1. Figure 1 thus shows the paired diagrams for this first reaction in metamorphism. At some temperature dolomite and quartz become incompatible with each other, reacting to form calcite and tremolite. The dolomite-quartz join of the first diagram disappears, and its place is taken by the join tremolite-calcite. These two joins have the crossed relation.[13]

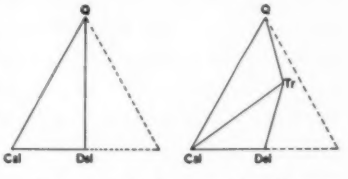

FIG. 1.—Paired composition diagrams of reaction equation 1.

[13] The crossed relation of the two joins in these projections is a reflection of the crossed relation of two planes in the space tetrahedron. These planes are the calcite-dolomite-silica plane and the calcite-tremolite-CO_2 plane.

If tremolite had the simplified anhydrous composition we have here used in plotting it, the reaction involved in this first step in metamorphism would be represented by the equation

$$3CaMg(CO_3)_2 + 4SiO_2 \rightleftharpoons CaMg_3(SiO_3)_4 + 2CaCO_3 + 4CO_2 . \quad (1)$$

As written, there are five reacting phases in a system of four components, and this would represent a univariant equilibrium. Just as in the simpler systems first considered there would, at any pressure, be a definite temperature at which all five phases could coexist, and, if at any pressure the temperature of a siliceous dolomite were raised, no change would occur until a definite temperature was reached. At this temperature the reaction would proceed until either dolomite or quartz had disappeared, that one surviving which was in excess of chemical equivalence in the original rock.

Again, if this equation accurately represented the reaction, we could by inspection of the equation write down the five possible four-phase assemblages that could occur above and below the reaction temperature at a given pressure. They would be:

a) dolomite + quartz + tremolite + calcite *b*) dolomite + quartz + tremolite + CO_2 *c*) dolomite + quartz + calcite + CO_2	lower temperatures
d) tremolite + calcite + CO_2 + dolomite *e*) tremolite + calcite + CO_2 + quartz	higher temperatures

As we have found in the simpler systems, here again the number of *minerals* formed upon metamorphism is one less than the number of components. The total number of phases is, of course, equal to the number of components (four), but one of them is always CO_2 (see the two higher-temperature assemblages), so that the number of minerals is three and our triangular projections in which CO_2 is not shown can accurately present the three coexistent mineral phases produced upon metamorphism in this four-component system.

Now unfortunately, as already noted, the theoretical aspects of the case are not quite so simple, because the formula for tremolite

is $Ca_2Mg_5H_2(SiO_3)_8$, and water is a component of the reacting system. The reaction is correctly written thus:

$$5CaMg(CO_3)_2 + 8SiO_2 + H_2O \rightleftharpoons Ca_2Mg_5H_2(SiO_3)_8 + 3CaCO_3 + 7CO_2 . \quad (1a)$$

The appearance of water in the equation has added a component to the system, making the number of components five, but has not necessarily increased the number of phases; the H_2O and CO_2 would form only one vapor phase, and the number of phases is only five. The system is therefore not univariant but divariant, and we cannot say, on theoretical grounds, that if we started with dolomite and silica (with some water), under a certain pressure, no formation of tremolite and CO_2 could occur until a definite temperature was attained and that the reaction would go to completion at this temperature. Theoretically, the reaction could take place over a range of temperatures, and not until another metamorphic mineral formed in addition to tremolite would we have a univariant condition. Actually no phase other than tremolite and calcite does normally appear to form in dolomites in the early (lowest temperature) stages of metamorphism. The observed relations are thus simpler than the above reasoning would suggest, and this is because one possibility has been neglected. If a liquid phase were present in addition to the vapor and the four solids, the six coexistent phases would constitute a univariant system and at any fixed temperature all the variables would have fixed values. The composition of the liquid phase, the partial pressures of both CO_2 and H_2O in the vapor, and therefore the total vapor pressure would all have definite values. At any fixed external pressure, then, a wet siliceous dolomite would experience no change until a definite temperature were reached, at which temperature the reaction of equation *1a* would proceed freely to the right until one of the phases—dolomite, quartz, or water (solution)—was exhausted. It is no doubt because the pressure-temperature conditions are ordinarily such as to permit the presence of a liquid solution that tremolite formation in the first step of metamorphism has all the attributes of a univariant reaction. A like remark applies to the other steps in which tremolite is one of the participating phases.

In taking the simplified anhydrous formula for tremolite, we have reduced the number of components by one, but we have also eliminated the possibility of a liquid phase[14] and thus reduced by one the number of possible phases. The conditions for univariancy are thus not changed. The use of the anhydrous formula for tremolite and of diagrams based upon it therefore involves in this respect no departure from fundamental principles and is justified by its convenience.

There are of course pressures at which wet siliceous dolomite might be heated that would not be adequate to enable retention of water (solution) up to temperatures at which formation of tremolite would proceed. Under such conditions the rock would simply be dehydrated and with further heating would suffer "dry" metamorphism, a condition perhaps corresponding with that prevailing during thermal metamorphism.[15] In thermal metamorphism of siliceous dolomite it is generally accepted that forsterite is the first phase formed. If this is true, then the reaction whereby it is formed cannot be an equilibrium reaction, for the phase assemblages involved should have represented in them only phases which, individually, can exist in equilibrium with dolomite and quartz. Obviously forsterite does not qualify since it cannot coexist with quartz. It would seem necessary to suppose that enstatite would be the first phase formed, with true equilibrium, in the thermal metamorphism of siliceous dolomite and that the first step involved would be represented by a diagram exactly like Figure 1, except for the substitution of enstatite for tremolite. Forsterite does indeed seem to be the first phase formed in the thermal metamorphism of dolomite (a failure of equilibrium).[16] The appearance of forsterite

[14] It would perhaps be preferable to say a "participating liquid phase," because in any of the reactions under consideration, including those involved in the metamorphism of siliceous limestone already discussed, a liquid phase may be present, which facilitates reaction yet is not essential to it and for the purposes of this discussion may be neglected because nonparticipating.

[15] We may interpret "dry" to mean not that no water is present but merely that no liquid water is present.

[16] Enstatite formation has been claimed in the ancient Grenville limestones of the Adirondacks (C. H. Smythe, Jr., *School Mines Quar.*, Vol. XVII [1895–96], p. 334). Modern studies do not confirm this observation.

in conditions where enstatite might be expected may be explained by assuming that, at the low temperatures involved, the first reaction step is too sluggish to be realized in the usual case, and only when the temperature is raised to a significantly higher value can any appreciable reaction occur. At that temperature forsterite formation is the necessary reaction.[17]

The complications that may be introduced by the hydrous character of tremolite in the usual first step of metamorphism may be further considered by setting down the possible phase assemblages of the true reaction represented by equation 1*a*. They are:

a) dolomite + quartz + solution + tremolite + calcite	}	lower
b) dolomite + quartz + solution + tremolite + vapor	}	tempera-
c) dolomite + quartz + solution + calcite + vapor	}	tures
d) tremolite + calcite + vapor + dolomite + quartz	}	higher
e) tremolite + calcite + vapor + dolomite + solution	}	tempera-
f) tremolite + calcite + vapor + quartz + solution	}	tures

When the phase assemblages are deduced with the aid of equation 1, which assumes the simplified composition of tremolite, the characteristic feature of the reaction is that dolomite and quartz cannot coexist above the temperature of the reaction (at given pressure). In the assemblages just listed the characteristic feature is that the three phases—dolomite, quartz, and solution—cannot coexist above the reaction temperature and, if the pressure is too low or the actual quantity of water available is too small (sediment too dry), that the first of these three phases to disappear at the reaction will be the solution, in which case dolomite and silica will survive the reaction, a condition exemplified by assemblage *d*. Thus, in the ultimate analysis, incompatibility of quartz and dolomite above a definite reaction point is a necessity only when conditions are such as to permit the existence of a pore solution both below and above the reaction temperature. If the rock "boils dry" below the reaction, no tremolite is formed; if it "boils dry" at the reaction point, some tremolite forms. In both circumstances quartz and dolomite sur-

[17] It is possible that the association enstatite-calcite is not a stable one and that dedolomitization by way of enstatite would be as definitely a failure of equilibrium as is that by way of forsterite.

vive to react only at a somewhat higher temperature with production of forsterite.[18] This is, as we have seen, not an equilibrium reaction. Production of enstatite is the expected equilibrium, but it is not usually realized. We find, then, that in the special circumstances discussed, there may be a discrepancy between the conclusions reached by assuming a "dry" formula for tremolite and those reached by using its true formula. No discrepancy of this kind appears at later steps involving tremolite for the reason that H_2O is on the left-hand side of the equation of the reaction we have just discussed, but it is on the right-hand side of the other reactions involving tremolite. The relation can be verified by setting down the phase assemblages possible at the subsequent reaction points, using the true formula for tremolite, but this will not be done here. Thus, although there are certain conditions, as discussed previously, which import an exception to the statement that quartz and dolomite become incompatible at a definite temperature (at given pressure), there are no exceptions to the statement that tremolite and dolomite become incompatible at a definite temperature in the step next to be considered nor to the statement that tremolite, forsterite, and quartz become incompatible at a definite temperature in the subsequent step. It will not be necessary, therefore, to discuss the significance of the true composition of tremolite in connection with those steps. The simplified composition which can be plotted in the tetrahedron gives the same result and will be used without further comment in discussing these steps.

The next step in metamorphism is indicated by the set of triangular planes next encountered in the tetrahedron by lines coming from the CO_2 apex (decarbonation). The set of planes is shown in the second diagram of Figure 2, which demonstrates that this step is due to the reaction of tremolite and dolomite to form forsterite and calcite (with CO_2). This is the relation indicated when tremolite is assigned the composition $CaMg_3(SiO_3)_4$ and so plotted, but, as we have seen, no difference in the deduced phase equilibria is

[18] It is perhaps a condition such as this that has given rise to metamorphism which is mineralogically intermediate between thermal and regional as discussed by Alfred Harker from Skye in his text, *Metamorphism* (London: Methuen & Co., 1932), pp. 85 and 86.

introduced by making this simplifying assumption. The simplified equation then is:

$$CaMg_3(SiO_3)_4 + 5CaMg(CO_3)_2 \rightleftharpoons 6CaCO_3 + 4Mg_2SiO_4 + 4CO_2. \quad (2)$$

The phase assemblages are:

a) tremolite + dolomite + calcite + forsterite	lower temperature
b) tremolite + dolomite + calcite + CO_2	
c) tremolite + dolomite + forsterite + CO_2	
d) calcite + forsterite + CO_2 + tremolite	higher temperature
e) calcite + forsterite + CO_2 + dolomite	

Again only three *mineral* phases can coexist after this step in metamorphism, and our triangular diagram accurately depicts the mineral assemblages. Figure 2 thus shows the paired diagrams for this reaction. The assemblage tremolite + calcite + quartz survives. The join dolomite-tremolite disappears and is replaced by the join calcite-forsterite, which has the crossed relation to it. The fundamental feature of this step is that tremolite and dolomite can coexist below it but not above it.

The next set of triangular planes within the tetrahedron is shown in projection in the second diagram of Figure 3, which demonstrates that the next step in metamorphism involves the formation of diopside according to the equation

$$CaMg_3(SiO_3)_4 + 2CaCO_3 + 2SiO_2 \rightleftharpoons 3CaMgSi_2O_6 + 2CO_2. \quad (3)$$

The phase assemblages are:

a) tremolite + calcite + quartz + diopside	lower temperature
b) tremolite + calcite + quartz + CO_2	
c) diopside + CO_2 + tremolite + calcite	higher temperature
d) diopside + CO_2 + tremolite + quartz	
e) diopside + CO_2 + calcite + quartz	

The assemblages calcite-forsterite-dolomite and calcite-forsterite-tremolite survive this step. Again only three mineral phases can

coexist in any assemblage after this reaction. We have here three different mineral assemblages capable of being formed, whereas in former reactions there have been only two. In other respects this step is somewhat different from the earlier ones, though fundamental factors are the same. For example, the paired diagrams for this reaction (Fig. 3) show that three minerals react to produce one mineral, and in consequence of this fact the composition points of the three reacting minerals—calcite, tremolite, and quartz—form a triangle with the point for the product of their reaction, diopside, inside that triangle. In the other reactions two minerals reacted to

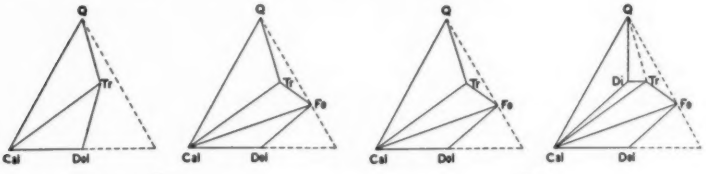

FIG. 2 FIG. 3

FIG. 2.—Paired composition diagrams of reaction equation 2
FIG. 3.—Paired composition diagrams of reaction equation 3

form two other minerals, and the two joins concerned had the crossed relation. The significant feature of this step of metamorphism is the coexistence of the *three* phases—calcite, tremolite, and quartz—below it but not above it.

One feature of Figure 3 as drawn may require comment. In all diagrams there are certain broken lines which lie at compositions with which we are not concerned here and are shown as broken lines for that reason. Since attention is confined to siliceous dolomite and dolomitic lime, more magnesian material being excluded from consideration, most of these lines emanate from the MgO corner of the diagram, but the line joining quartz and tremolite in Figure 3 is in the same class. With diopside present, no tremolite can appear together with quartz unless the original carbonate was more magnesian than dolomite, as a glance at the figure will show. A highly siliceous dolomite or a dolomitic quartzite will here give a diopside-quartz rock, and such a rock is in its final state with respect to metamorphic processes. It will not be affected at any of the later steps.

Indeed this is obviously true of any of the mixtures when they have been converted entirely to silicates, since decarbonation is complete and all the steps involve decarbonation.[19]

The next set of planes in the tetrahedron, encountered in our graphical decarbonation, is shown in projection in the second diagram of Figure 4. The change from the first diagram of Figure 4 consists in the disappearance of the join calcite-tremolite and the appearance of the join diopside-forsterite, indicating a reaction according to the equation

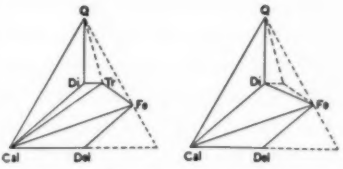

FIG. 4.—Paired composition diagrams of reaction equation 4.

$$2CaCO_3 + 3CaMg_3(SiO_3)_4 \rightleftharpoons 5CaMgSi_2O_6 + 2Mg_2SiO_4 + 2CO_2 . \quad (4)$$

The phase assemblages possible are:

a) calcite + tremolite + diopside + forsterite *b*) calcite + tremolite + diopside + CO_2 *c*) calcite + tremolite + forsterite + CO_2	lower temperature
d) diopside + forsterite + CO_2 + calcite *e*) diopside + forsterite + CO_2 + tremolite	higher temperature

The fundamental feature of this step is, of course, the possibility of the coexistence of calcite and tremolite below it but not above it. We already had a step at which tremolite and calcite became incapable of coexistence if quartz were present also. The conditions involved in both of these steps are to be carefully distinguished from the conditions under which tremolite becomes unstable as such. With this we are not concerned here, for, though tremolite can still exist at higher temperatures at the given pressure, it cannot occur in materials which are no more magnesian than dolomite, and to such we have confined our discussion.[20] The assemblage *e* illustrates this point.

[19] Reactions among the silicates themselves are, of course, not impossible at higher temperatures, but no such reactions seem to exist except one to be mentioned later.

[20] The instability of tremolite and related amphiboles in higher grades of metamorphism has, however, much importance for the subject in general (see C. E. Tilley,

It is a possible assemblage on the high-temperature side of the reaction step now under consideration, but it is confined to compositions having MgO in excess of CaO (molal). This assemblage is shown in Figure 4 to make clear the connection with the preceding figure, but broken lines are used because it concerns compositions excluded from consideration, and the assemblage is omitted in subsequent figures. Indeed, with this step completed, we have no further need to consider tremolite. We gladly speed the parting guest, for all subsequent reactions are rigorously of four components, and we no longer need to indulge in the approximations which tremolite has rendered necessary.[21]

It is important to emphasize that the step whose consideration we have just completed is the final step in what is usually termed "regional metamorphism." Metamorphism is carried farther only under the higher temperature (or lower pressure) conditions of thermal metamorphism.

We now come to a step in metamorphism which is concerned with a reaction in the CaO-MgO-CO_2 system. It occurs at the temperature at which dolomite becomes unstable at the given pressure. We have already had a step in which dolomite became unstable in contact with tremolite; now dolomite as such becomes unstable. It should be emphasized that, although this reaction involves the dropping-down from one plane to another on lines emanating from the CO_2 apex (decarbonation) in exactly the same manner as in each preceding step, there is, nevertheless, nothing in the geometrical relations in the tetrahedron or indeed in the nature of things to determine that this will be the next step. A reaction in some other part of the tetrahedron might be the next, as far as can be determined from these general considerations, and it is solely the accumulated knowledge of metamorphic rocks which leads us to place

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Geol. Mag., Vol. LX [1923], p. 418; E. Posnjak and N. L. Bowen, *Amer. Jour. Sci.*, Vol. XXII [1931], pp. 203–14).

[21] It may not be amiss here to state some of the considerations which led to the exclusion of the more magnesian compositions from study. In the first place, they are quantitatively much less important, but more cogent was the fact that three hydrous phases—talc, serpentine, and anthophyllite—would have appeared, and each would have introduced the same difficulties that made tremolite unwelcome.

the decomposition of dolomite next. This geological evidence will be mentioned in discussing the step immediately following.

The reaction concerned in the present step is:

$$CaMg(CO_3)_2 \rightleftharpoons CaCO_3 + MgO + CO_2, \qquad (5)$$

a four-phase reaction in a three-component system and therefore univariant. The phase assemblages are:

a) dolomite + calcite + periclase
b) dolomite + calcite + CO_2 } lower temperature
c) dolomite + periclase + CO_2

d) calcite + periclase + CO_2 } higher temperature

As a result of the disappearance of dolomite, the dolomite-forsterite join must disappear and compositions in the calcite-dolomite-forsterite plane drop down to positions in the calcite-periclase-forsterite plane as illustrated in Figure 5. Henceforth it becomes necessary to use full lines in the MgO corner of the successive triangles. The other phase assemblages, namely, calcite-forsterite-diopside and calcite-forsterite-silica, remain unchanged.

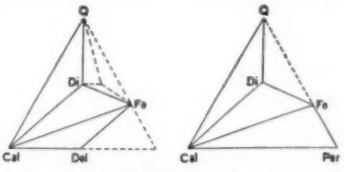

FIG. 5.—Paired composition diagrams of reaction equation 5.

The next step in metamorphism involves the formation of wollastonite in appropriate compositions and is, in one major respect, analogous to the last. It is concerned with a reaction in one of the three-component systems, in this case the system CaO-SiO_2-CO_2, and since, as before, these compositions are off by themselves on a side of the tetrahedron, their relations cannot be deduced from the positions of overlapping planes within the tetrahedron. Therefore, the fact that the reaction involving the formation of wollastonite is the next step is determined entirely from recorded knowledge of metamorphic rocks. More specifically, metamorphic aureoles indicate that dolomite is transformed to a periclase marble under conditions which permit beds of quartzose limestone to recrystallize as

such without formation of a wollastonite marble.[22] Both these reactions precede those involving the formation of the minerals of lower silica ratio to be discussed later. Especially is it true that the step involving wollastonite formation must precede that in which there is formation of akermanite, for otherwise akermanite would find itself joined to quartz—an impossible association.

The reaction is then as follows:

$$CaCO_3 + SiO_2 \rightleftharpoons CaSiO_3 + CO_2 . \qquad (6)$$

This is, of course, the same reaction already considered in connection with the metamorphism of siliceous limestone. It is important to note, therefore, that all the steps we have hitherto considered in the metamorphism of siliceous dolomitic limestone take place at lower temperatures (indicate a lower grade of metamorphism) than does the formation of a wollastonite marble from a siliceous limestone. Siliceous limestone suffers no change under conditions which have already brought about, progressively, several steps in the metamorphism of siliceous dolomitic limestone or dolomite. This contrast is, of course, in accord with the experimental demonstration that magnesian carbonates lose their CO_2 with greater ease than does calcium carbonate.

The new diagram is the second diagram of Figure 6. All compo-

[22] In point of fact the evidence of rocks upon this question is somewhat conflicting. To metamorphism at moderate depth the above statement applies. Thus, in Skye, Tertiary granites have developed periclase in dolomitic limestones under no great cover, but no wollastonite has developed even about flint nodules (Harker, *Tertiary Igneous Rocks of Skye*, p. 150). On the other hand, in the Grenville limestones of the Canadian shield wollastonite is produced at some contacts (though usually in this deep-seated metamorphism the diopside stage is not passed) without the appearance of periclase (or its alteration product, brucite) at these contacts. The deep-seated metamorphism is complicated by notable introduction of foreign material such that often too much silica would be present for the formation of periclase even though it would otherwise be possible. Thus diopside appears instead, or, with introduction of alumina, spinel. Nevertheless, it does appear that evidence of the formation of periclase would be more frequent (brucite marbles are not unknown, see M. F. Goudge, "Limestones of Ontario," *Canada Bur. Mines Bull. 781* [1938], pp. 130–32) if it really could take place before wollastonite formation under these deep-seated conditions. It is suggested, therefore, that, while periclase formation appears to precede that of wollastonite at shallow depths, the reverse order may prevail at greater depths. This possibility is further discussed in connection with the diagram of P-T curves.

sitions lying in the triangle quartz-diopside-wollastonite have reached their final state. Naturally only those assemblages which have calcite can suffer further metamorphism involving decarbonation.

Of this more advanced metamorphism the first step is ordinarily that concerned with the formation of monticellite. It is true that experimental studies show that monticellite and diopside cannot coexist at high temperatures but are cut off from each other by the forsterite-akermanite join, and, if these same relations persisted at lower temperatures, the step we are now considering would be preceded by that involving the formation of akermanite. Metamorphic rocks, such as the blocks of limestone at Vesuvius, show, however, that monticellite can occur with diopside or at least with a pyroxene close to diopside. Moreover, in certain alnoites a diopside-rich pyroxene is replaced by monticellite giving rims of monticellite about pyroxene without any interposition of melilite (akermanite) between them.[23] In this late magmatic stage, then, we have the same equilibrium as in metamorphism, but at full magmatic temperatures we have relations that suggest the existence of the equilibrium determined experimentally at high temperatures, for in melilite basalts we have phenocrysts of melilite (fairly rich in akermanite) and olivine (rich in forsterite) growing side by side. All these facts point to the existence of the silicate equilibrium

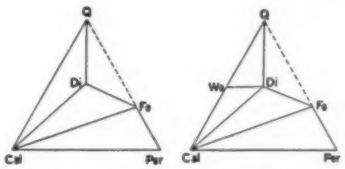

FIG. 6.—Paired composition diagrams of reaction equation 6.

$$\text{diopside} + \text{monticellite} \rightleftarrows \text{forsterite} + \text{akermanite},$$

a univariant reaction which goes in the direction from left to right with rising temperature. There may be a pressure sufficiently high to permit the existence of diopside and forsterite in the presence of calcite at a temperature which would lie above that of this silicate equilibrium at that pressure. If so, under this and higher pressures

[23] Bowen, "Genetic Features of Alnoitic Rocks from Isle Cadieux, Quebec," *Amer. Jour. Sci.*, Vol. III (1922), pp. 1–34.

akermanite and not monticellite would succeed wollastonite in the list of metamorphic minerals formed at successive steps. Actually, under deep-seated (high pressure) conditions the temperature is probably never high enough to carry metamorphism beyond the wollastonite step, so the question whether akermanite would come in before monticellite may have no practical importance, but that relation is indicated as a theoretical possibility in the P-T curves of Figure 14. Certainly in well-studied examples monticellite occurs with diopside, and the reaction involving formation of monticellite is therefore to be regarded as ordinarily the next step in metamorphism.

The reaction is expressed by the equation

$$CaMgSi_2O_6 + Mg_2SiO_4 + 2CaCO_3 \rightleftharpoons 3CaMgSiO_4 + 2CO_2 . \quad (7)$$

The phase assemblages are:

a) diopside + forsterite + calcite + monticellite	lower temperatures
b) diopside + forsterite + calcite + CO_2	
c) monticellite + CO_2 + diopside + forsterite	higher temperatures
d) monticellite + CO_2 + diopside + calcite	
e) monticellite + CO_2 + forsterite + calcite	

This is, therefore, another step of the kind in which three minerals give rise to one mineral. Forsterite no longer occurs in association with diopside in the mixtures here under consideration, a fact indicated by the dotted join in Figure 7, which shows the paired diagrams for this reaction. Only in mixtures richer in magnesia can they occur together. The significant feature of this step in metamorphism is that the three phases—diopside, forsterite, and calcite—can no longer coexist.

Proceeding to higher temperatures, at a given pressure, the next reaction suggested by the tetrahedron is the formation of akermanite.[24] The equation for possible akermanite development is:

$$CaMgSi_2O_6 + CaCO_3 \rightleftharpoons Ca_2MgSi_2O_7 + CO_2 . \quad (8)$$

[24] The relations here are actually much more complicated, and ordinarily a complex melilite phase comes in at this point. An adequate approximation for general purposes is given by writing equations for akermanite formation. The complications are discussed more fully in connection with the P-T diagrams given later.

Though involving phases whose composition lies within the tetrahedron, it represents a limiting case and is of only three components. The phase assemblages are:

a) diopside + calcite + akermanite
b) diopside + calcite + CO_2 } lower temperature

c) akermanite + CO_2 + diopside
d) akermanite + CO_2 + calcite } higher temperature

The significant feature is that diopside and calcite can now no longer coexist. Figure 8 shows the paired diagrams.

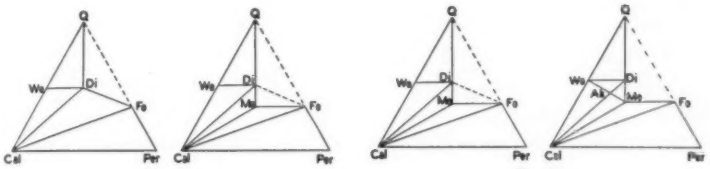

FIG. 7 FIG. 8

FIG. 7.—Paired composition diagrams of reaction equation 7
FIG. 8.—Paired composition diagrams of reaction equation 8

At a somewhat higher temperature, according to the indications of planes in the tetrahedron, another reaction resulting in the formation of monticellite takes place. This is a crossed reaction for which the equation may be:

$$Mg_2SiO_4 + CaCO_3 \rightleftharpoons CaMgSiO_4 + MgO + CO_2 . \qquad (9)$$

The phase assemblages are:

a) forsterite + calcite + monticellite + periclase
b) forsterite + calcite + monticellite + CO_2
c) forsterite + calcite + periclase + CO_2 } lower temperatures

d) monticellite + periclase + CO_2 + forsterite
e) monticellite + periclase + CO_2 + calcite } higher temperatures

The significant feature is that calcite and forsterite cannot coexist above this temperature; indeed, forsterite cannot exist except in compositions with a higher Mg:Ca ratio than that of dolomite. Fig-

ure 9 shows the paired diagrams for the reaction, and in them the join forsterite-calcite and the join monticellite-periclase naturally have the crossed relation.

We have now come to a stage where metamorphism is complete for the greater part of the composition range we set out to consider. Siliceous dolomite, for example, has now reached its final state, and it may not be amiss to call attention to the different assemblages that will be formed, according to the different proportions of silica in the original dolomite. These assemblages can be read from the second diagram of Figure 9. With no original silica the product would consist of calcite and periclase; with silica up to 33.3 mol per cent, of calcite, periclase, and monticellite; with silica between 33.3 and 50 per cent, of monticellite and diopside; and with more than 50 per cent silica, of diopside and quartz.

The only compositions that can suffer further metamorphism are certain lime-rich types which now consist either of calcite, akermanite, and wollastonite or of calcite, akermanite, and monticellite. There are two possible decarbonation reactions. Wollastonite and calcite react to form spurrite and CO_2. Akermanite and calcite react to form merwinite and CO_2. The compositions concerned in the one reaction are quite independent of those concerned in the other and are therefore nonoverlapping in the tetrahedron. Geometrical relations do not decide which will take place first. We must turn to mineral associations for suggestions. If we assume that formation of merwinite is the next step, then in our next diagram a join merwinite-wollastonite would appear, and it would cut off akermanite from spurrite. In the original description of the type material for merwinite from Crestmore, California, Larsen and Foshag, after describing the minerals that occur "in interlocking grains" with merwinite, state that wollastonite is "less intimately associated with merwinite."[25] Moreover, spurrite is, there and elsewhere, associated with melilites which, while they are far from pure akermanite, are nevertheless the same crystalline phase and contain much of the akermanite molecule. These facts suggest that akermanite should not be cut off from spurrite but that merwinite should be cut off from wollastonite. We therefore take as our

[25] E. S. Larsen and W. Foshag, *Amer. Min.*, Vol. VI (1921), p. 144.

next step the spurrite-forming reaction, which introduces the join, spurrite-akermanite and will cut off merwinite from wollastonite. These relations are shown in Figure 10. The equation for the reaction has already been given but is repeated here and numbered in accordance with its position in the present series.

$$3CaCO_3 + 2CaSiO_3 \rightleftharpoons 2Ca_2SiO_4 \cdot CaCO_3 + CO_2 . \qquad (10)$$

It should not be supposed that there is anything exceptional about this step in which spurrite is formed. It entails a dropping-down from one set of planes to another in the tetrahedron, just as do all

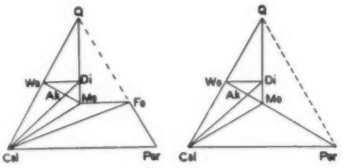

FIG. 9

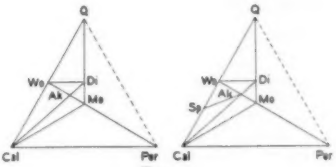

FIG. 10

FIG. 9.—Paired composition diagrams of reaction equation 9

FIG. 10.—Paired composition diagrams of reaction equation 10

the reactions, but so would the merwinite-forming reaction also, and the relations of the planes are such as to necessitate appeal to mineral associations to decide which step comes first.

We now come to the step in which merwinite is formed according to the equation

$$Ca_2MgSi_2O_7 + CaCO_3 \rightleftharpoons Ca_3Mg(SiO_4)_2 + CO_2 . \qquad (11)$$

Though the compositions involved lie within the tetrahedron, it is another example of a special limiting case and is of only three components. With four reacting phases it is univariant, and the phase assemblages are:

a) akermanite + calcite + merwinite
b) akermanite + calcite + CO_2 } lower temperature

c) merwinite + CO_2 + akermanite
d) merwinite + CO_2 + calcite } higher temperature

The significant feature is that akermanite and calcite cannot coexist above this step. The paired diagrams of the reaction are shown in Figure 11.

In the next step in metamorphism larnite is formed as a result of the reaction of wollastonite and spurrite, a step already considered in connection with limestone proper. Its effect as evinced in the present system is shown in Figure 12. The equation for the reaction is:

$$CaSiO_3 + 2Ca_2SiO_4 \cdot CaCO_3 \rightleftarrows 3Ca_2SiO_4 + CO_2 . \qquad (12)$$

There is perhaps yet another step. Larnite and merwinite are cut off from each other in Figure 12 by the spurrite-akermanite join.

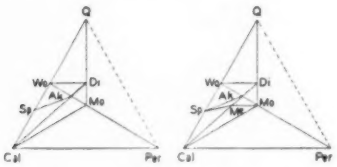

FIG. 11

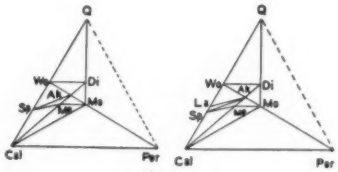

FIG. 12

FIG. 11.—Paired composition diagrams of reaction equation 11

FIG. 12.—Paired composition diagrams of reaction equation 12

The relations shown at the one locality where larnite has been found suggest that larnite and merwinite can coexist. We may suppose, therefore, that the following reaction takes place:

$$2Ca_2SiO_4 \cdot CaCO_3 + Ca_2MgSi_2O_7 \rightleftarrows 2Ca_2SiO_4 + Ca_3MgSi_2O_8 + CO_2 . \qquad (13)$$

The phase assemblages are:

a) spurrite + akermanite + larnite + merwinite	lower temperature
b) spurrite + akermanite + larnite + CO_2	
c) spurrite + akermanite + merwinite + CO_2	
d) larnite + merwinite + CO_2 + spurrite	higher temperature
e) larnite + merwinite + CO_2 + akermanite	

The new diagram showing the higher-temperature assemblages is given in Figure 13. With this step we have reached the highest

known step in metamorphism. No further changes are known to occur, and most of the compositions of the system, subjected to the conditions prevailing at this stage, would suffer no change from the condition established in some preceding step. Calcite can at this highest temperature coexist with spurrite, merwinite, monticellite, or periclase. Further decarbonation reactions are conceivable, say, the formation of tricalcic silicate or of lime itself, but they are not known to occur, a fact that will be discussed more fully at a later point.

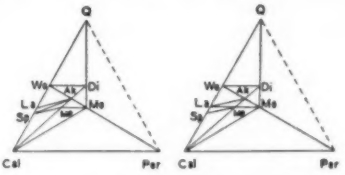

FIG. 13.—Paired composition diagrams of reaction equation 13.

THE THIRTEEN STEPS

Reasoning based on a combination of observed mineral associations and theoretical phase-equilibrium relations thus leads to a picture of the metamorphism of carbonate rocks as capable of exhibiting thirteen steps. All these steps are univariant reactions (if we conveniently forget that there may be some departure from this condition in those early steps which involve tremolite), resulting in the evolution of CO_2, and the temperature at which they will occur therefore depends upon the applied pressure of CO_2. For each of the reactions a curve can be drawn which gives the temperature at which the reaction will go forward at any pressure—a P-T curve. In Figure 14 is shown, in purely schematic manner, the relation between the several P-T curves for these reactions. The curve for the reaction taking place at any step always lies, at any pressure, at a *lower* temperature than does the curve for the reaction of the next higher step, which is, indeed, the reason why it is here called a higher step, attention being focused upon the temperature aspect. It is clear also that the curve for any step lies at a *higher* pressure at any given temperature than the curve for the next higher step. Now, although at each step a number of different assemblages can exist below it and a number above it, some assemblages persisting through several, nevertheless each step has a characteristic feature, which indeed depends upon the reaction taking place at that step. In all cases this fundamental feature is of the same general charac-

ter; a certain phase assemblage can exist below the step but not above it. Every step is thus characterized by the disappearance of a phase assemblage, each its own assemblage, and, although this fact has been pointed out in the discussion of each reaction, it is desirable to bring together here these fundamental features of each step.[26]

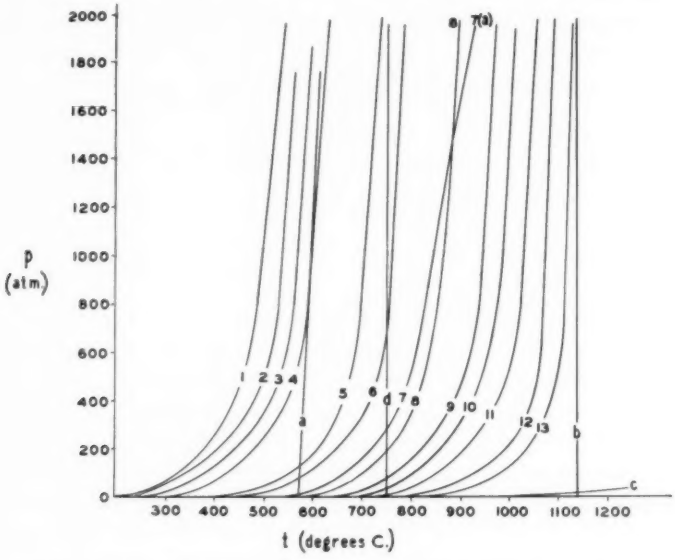

FIG. 14.—Curves *1–13* are pressure-temperature curves of the reactions of equations 1–13, respectively, and of Figs. 1–13, respectively. Curve *a* is the inversion curve α-quartz to β-quartz. Curve *b* is inversion curve wollastonite to pseudowollastonite and indicates approximate extreme temperatures of magmas. Curve *c* is dissociation pressure curve of $CaCO_3$. Line *d* is approximate upper temperature of granitic magmas.

The assemblages which can exist below each step but not above it are as shown in Table 1. At any given pressure we have, thus, thirteen points on a thermometer scale, and they are absolutely fixed, given that the compositions of all the mineral phases lie within

[26] It should perhaps be pointed out that there is no individual composition that could show all thirteen steps. The discussion applies to a carbonate formation in which different beds show a considerable range of proportions of calcite, dolomite, and silica, though certain calcite-rich beds could experience nearly all the steps.

the system under consideration. Nothing can detract from the complete generality of this aspect of the character of any step, viz., that a certain phase assemblage must disappear if that step has been attained and therefore that the survival of that assemblage indicates the failure of attainment of the conditions corresponding with that step. It matters not what other minerals are or were present, what solutions were circulating or what gases were streaming by, the persistence of, for example, wollastonite and calcite in interlocking association indicates that the conditions of step 10 were not attained. What is meant by "the conditions of step 10" is to be read from curve *10* of Figure 14. The implications of these inflexible relations can, indeed, be carried further. We started with siliceous limestone and dolomitic limestone and developed our discussion by considering changes in materials of fixed bulk composition (except with respect to CO_2), but in doing so it is to be hoped that no one will assume that we have joined the ranks of those who believe that there is no introduction of material in metamorphism. Although reached by that procedure, the conclusions indicated by the table of steps (Table 1) are applicable to any sort of material. The limestone might have been originally quite pure $CaCO_3$, the silica and magnesia introduced, and along with them many other materials, orthoclase and albite, say, or fluorine-bearing phases such as chon-

TABLE 1

TABLE OF STEPS

To left of curve *1*, i.e., below step	1	Dolomite and quartz
To left of curve *2*, i.e., below step	2	Dolomite and tremolite
To left of curve *3*, i.e., below step	3	Calcite, tremolite, and quartz
To left of curve *4*, i.e., below step	4	Calcite and tremolite
To left of curve *5*, i.e., below step	5	Dolomite
To left of curve *6*, i.e., below step	6	Calcite and quartz
To left of curve *7*, i.e., below step	7	Calcite, forsterite, and diopside
To left of curve *8*, i.e., below step	8	Calcite and diopside
To left of curve *9*, i.e., below step	9	Calcite and forsterite
To left of curve *10*, i.e., below step	10	Calcite and wollastonite
To left of curve *11*, i.e., below step	11	Calcite and akermanite
To left of curve *12*, i.e., below step	12	Spurrite and wollastonite
To left of curve *13*, i.e., below step	13	Spurrite and akermanite

drodite, yet the facts indicated in the table of steps will still apply. Indeed, the original rock need not have been a carbonate rock at all, but to any kind of a "soaked" rock or a vein-stuff the association limitations of the table of steps apply with equal force. Again the limestone might have been initially very impure, having argillaceous material as well as silica, yet the resulting aluminous phases, such as grossularite, vesuvianite, anorthite, etc., would not affect the maximum temperature of persistence (at fixed pressures) of the phase assemblages given in the table of steps. The amount of alumina present (or added) might, of course, be so great as to prevent the formation of some of the reference phases in all stages of metamorphism. This is, however, a different matter and leads to no ambiguity, for it is the presence of a certain mineral assemblage that is used as a criterion of grade; the absence of the assemblage is of no significance in that connection.

There is, of course, one class of material for which the conclusions reached require modification, and this is material which can enter into solid solution in the mineral phases formed. If, for example, ferrous iron replaces some of the magnesia of the original dolomite or if ferrous material were introduced in the metamorphic process, then the reaction which produces monticellite in step 7 would not take place at the same temperature as it would with pure nonferrous materials nor would it take place at a fixed temperature. It would be spread through a range of temperature, at a given pressure, because the reaction is no longer univariant. This would be true of every step in which the material might participate if that step involved magnesioferrous phases. It would not be true of steps 6, 10, and 12 provided the initial material had the appropriate composition to experience these steps.[27] Apparently, if we may judge from the evidence of rocks, the amount of spreading-out of these steps from such causes is not serious, at least with moderate content of iron or other similar material,[28] and probably does not cause overlapping and con-

[27] Although wollastonite takes $FeSiO_3$ and indeed $MgSiO_3$ into solid solution at high temperatures, the amount of such solution at most metamorphic temperatures is very small, and wollastonite may for all practical purposes of the present discussion be regarded as of fixed composition.

[28] Alumina has already been mentioned as not affecting equilibrium in so far as it goes to form separate phases, such as grossularite, etc., but it will, of course, affect equilibrium when it enters into solid solution in any of the phases of the reference

fusion of steps. Of course, if the amount of foreign material present, either originally or newly added, is such that, say, the pyroxene of step 7 could not appropriately be referred to as diopside but is perhaps more appropriately to be called augite or hedenbergite, the scheme here propounded would be entirely inapplicable. The reason for stressing the fixed character of these steps in the "pure" materials is that here we have some definite points to which we may tie geologic temperatures—points whose relative position only is suggested by this study but whose absolute position may be susceptible of laboratory determination. And when we speak of points it will be realized, of course, that these steps could be assigned definite temperature values only if the pressure were known, so that the aim of the laboratory study would obviously be the determination of the P-T curve for each of these reactions, the curves that are shown schematically in Figure 14. When this had been done for the "pure" mixtures of the system upon which attention is here focused, the direction and magnitude of the changes brought about when other substances enter into solid solution in the "pure" phases could then be sought. The pressure-temperature relations ascertained would furnish valuable information not only on temperatures but also on pressures prevailing during various geologic processes, igneous, metamorphic, and hydrothermal. In the meantime we have, from the theoretical development alone, some indications as to relative temperatures and pressures.

THE METAMORPHIC MINERALS

The reactions at which certain phase assemblages must disappear furnish, as we have seen, evidence as to temperatures, but it is in

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assemblages. The most important effect of this kind is its formation of gehlenite, which goes into solid solution in akermanite; indeed the mineral most commonly encountered in metamorphic rocks is closer to gehlenite than to akermanite. The step involving formation of melilite is thus considerably more complicated than has been indicated in the theoretical development where only the akermanite end-member could be considered possible. There is a further complication in the indications that akermanite may be incapable of existence at low temperatures (N. L. Bowen, J. F. Schairer, and E. Posnjak, *Amer. Jour. Sci.*, Vol. XXVI [1933], p. 276), but this is not unconnected with the situation just mentioned because apparently gehlenite-akermanite solid solutions can exist at lower temperatures than can akermanite itself. Even with these complications it is apparent that the melilite phase behaves in the metamorphic process in approximately the manner deduced for the end-member of this phase, akermanite.

some measure of a negative character. The existence of a certain phase assemblage shows that a certain temperature *has not been attained*, and the conclusion is absolutely rigorous, given "purity" of the phases. It would be gratifying if we could find in these reactions some temperature evidences of a positive character, in short, if we could say that a certain temperature *has been attained*. Analysis of the situation shows that we cannot make statements of this character that can be rigorously supported by theoretical considerations, and yet the reactions are not without some value in this capacity.

Each of the reaction steps is characterized by the disappearance of a phase assemblage and some of them by the first appearance of a phase. The question is, "Can the *appearance* of a phase be used as a criterion of temperature in the same manner that the *disappearance* of a phase assemblage serves in this capacity?" and the answer to this question has been anticipated in the concluding sentence of the preceding paragraph.

The mineral phases produced in the metamorphism of siliceous (or silicified) dolomitic limestones are listed below in the order of their production at the thirteen steps. There are only ten of them because some of the steps are concerned with reactions between phases earlier produced. They are:

1. Tremolite
2. Forsterite
3. Diopside
4. Periclase
5. Wollastonite
6. Monticellite
7. Akermanite
8. Spurrite
9. Merwinite
10. Larnite[29]

The arrangement is in the order of their production with rising temperature, but it must be strongly emphasized that there is nothing inherently of a high-temperature character in the minerals with the higher numbers. All indications are that any of these minerals is stable at ordinary temperatures.[30] It is only with respect to their

[29] As an aid in remembering the order of these ten minerals the following ten-word jingle is suggested:

Tremble, for dire peril walks,
Monstrous acrimony's spurning mercy's laws

[30] This statement does not, of course, apply to Ca_2SiO_4 in the form larnite, for its inversion to a stable low-temperature form can be induced merely by the blow of a

production in metamorphism of carbonates, assumed as purely thermal or substantially so, that these minerals can be thus arranged in an ascending temperature series. In the discussion of the several steps in metamorphism the mineral assemblages have been given, and in each case the assemblage *a* comprises all the *mineral* phases involved in the reaction. The phase which we have spoken of as produced by the reaction is perfectly stable in contact with all the other mineral phases concerned in the reaction at temperatures *below* the reaction.

We could affirm that the formation of a certain mineral indicated the attainment of a certain temperature only in the special instances where we could be perfectly sure that the initial material was a siliceous dolomitic limestone and was metamorphosed by heat alone or with no more than an insignificant amount of immobile pore solution to facilitate reaction. And indeed our conclusion would in such circumstances be as rigorous as one based on the *failure of disappearance* of certain phase assemblages. However, in any individual case we may not make these assumptions as to the simplicity of conditions. There may have been circulating solutions, and here is where the case based on failure of disappearance of a phase assemblage manifests its superiority over the case based on the *appearance* of a phase. Evidence of the presence of circulating solutions of whatever character can, as we have found, affect in no manner the significance to be attached to the survival of a phase assemblage, indeed evidence of that kind would strengthen the case, since the solutions would indubitably facilitate such reactions between phases as could have occurred under the prevailing pressure-temperature conditions. But in connection with the significance to be attached to the appearance of a new phase the mere possibility of the presence of circulating solutions is of importance because such solutions could introduce a phase or even induce its formation at temperatures far below that at which it would be produced in that simple type of metamorphism assumed in the foregoing discussion, the simplicity being there assumed, of course, for the purpose of discovering laws or generalizations.

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hammer. The significant point is that the compound Ca_2SiO_4 is stable at low temperatures, as are all other compounds listed.

It has already been shown that the metamorphic minerals formed in the higher steps are not inherently of a high-temperature character, so the fact that solutions of the right kind might introduce and deposit one or more of these minerals at relatively low temperatures need not be enlarged upon, but the fact that solutions could induce the formation of these minerals at relatively low temperatures from materials present in the rock may require some comment. In this case, indeed, the solution need not be of any highly specialized character. There is only one requirement, viz., that the solution can dissolve CO_2, and it therefore must not be saturated with CO_2 for the prevailing conditions. We might assume in an extreme and wholly imaginary case a solution of caustic alkali which could freely absorb CO_2 and reduce its pressure to a negligible value. In the presence of such a solution even the "highest" of the reactions could evidently take place at relatively low temperature. Or we might assume as another extreme the circulation of pure water. It has significant solvent power for CO_2 and, if water were circulating with sufficient rapidity (in sufficient quantity), the effective pressure of CO_2 would be reduced sufficiently to produce significant lowering of the temperature below that at which each of the steps of metamorphism would "normally" proceed.[31] In any of these cases it is necessary to assume circulation of solutions; in some cases, very vigorous circulation. The mere presence of a minute amount of immobile pore solution, however potent it might be in absorbing CO_2, would not affect the simple picture originally presented, for a minute amount of solution would have its powers in that direction exhausted when only a negligible amount of reaction of the rock constituents had occurred, and any significant reaction would depend upon the factors presented in the initial discussion.

Now, when we examine the actual occurrences of the ten minerals of the metamorphic series, we find that the limitations upon their use as temperature indicators are perhaps not so important as this lengthy discussion might suggest. On the whole, it would appear that conditions ordinarily approach more closely the simple picture involving only insignificant amounts of solution rather than a con-

[31] A streaming-through of gases accomplishing a washing-out of the CO_2 would plainly have the same effect.

dition involving free circulation of great quantities of solution, or else that such solutions as circulate have relatively little power of carrying away CO_2, perhaps because they are already saturated with it or nearly so. If, for example, we examine the occurrences of these metamorphic minerals, we find that at the relatively low temperatures (and high pressures) of regional metamorphism the diopside stage is never passed; at the somewhat higher temperatures of the contact zones about granites, which come from the coolest of magmas, the wollastonite stage may be attained but not passed. It is only at the hotter contacts of syenitic or granodioritic masses that we begin to get members higher in the series, and the highest members are associated only with basic, for the most part basaltic, rocks. Temperature is, of course, not the only controlling factor. As the P-T curves show, a low pressure acts in the same direction as a high temperature; therefore, we may expect to find the higher members of the series at the contacts of hypabyssal intrusives, and these expectations are borne out by the actual occurrences. It is not necessary to adhere to the view that mere depth and therefore weight of overburden fixes the pressure in order to see significance in the depth factor as exerting a control over the mineral character. Porosity of the rocks, existence of open fissures, and like factors will play a role in fixing the effective pressure of CO_2, but they are in large measure functions of depth. We find, therefore, that broad general correspondence of the mineral characters with depth-temperature relations which has just been pointed out, but in the detailed relations about any individual intrusive mass simplicity may be lacking. There may be no simple arrangement, with an inner zone showing the "highest" minerals and successive outer zones showing progressively "lower" minerals. Local channels, proximity to which provided relatively easy escape for CO_2 and perhaps relatively easy ingress of hot solutions, might lead to the formation of localized deposits of high-grade minerals even in outer portions of a metamorphic aureole.

There is one other feature of our list of ten metamorphic minerals that is probably connected with the conditions of their origin and is therefore worthy of mention here. If they are arranged in the supposed order of their production with increasing temperature, as has

already been done, and if beside each of them is placed the date of its original discovery or recognition as a distinct mineral species, it is found that they are also substantially in the order of their discovery.

Tremolite	1796	Monticellite		1831
Forsterite	1824	Akermanite	artificial	1884
Diopside	1806		natural	1910
Periclase	1841	Spurrite		1908
(Brucite, 1814)		Merwinite		1921
Wollastonite	1822	Larnite		1929

Now it is scarcely to be doubted that the order of their discovery is also the order of their abundance in nature, those identified long ago being commonly occurring minerals, while those recognized only recently are comparatively rare species. It seems legitimate to suppose then that natural relations are such that those conditions favoring formation of the lower members of the series occur frequently, whereas those favoring formation of the higher members occur but seldom. Expressing these facts in terms of pressure-temperature relations, we may say that the temperatures are very frequently high enough to produce the low members of the series, less frequently high enough to produce the intermediate members, seldom high enough to produce the upper members and even then usually only at relatively low pressures. The order of discovery of the minerals, interpreted as a measure of their relative abundance, may thus be regarded as confirming the deductions as to the conditions and order of their formation with rising temperature, because we know that, for metamorphism, low temperatures are very frequently available and may be widespread in the crust, that this is less true of intermediate temperatures, whereas high temperatures are but seldom available for metamorphic processes and are strongly localized in fairly small masses of rock.

The conclusion may be repeated, then, that disturbing complications do not, ordinarily, characterize the processes of formation of these ten metamorphic minerals and that they may be used with reasonable assurance as indicators of temperature, even though it is necessary to turn to the list of thirteen phase assemblages for absolutely reliable information upon temperature, or, better stated, upon pressure-temperature relations.

RETROGRESSIVE METAMORPHISM

The phase reactions that occur at each of the thirteen steps are reversible and would be reversed if all the phases on the high-temperature side of the equation were retained. In each case one of these phases is CO_2, and the very fact that the reaction occurred at all is evidence that the applied pressure was not adequate to permit retention of this CO_2. With CO_2 gone or present in inadequate concentration (pressure), the reaction characterizing a step will not be reversed, as the rock cools through the temperature of the step, and the metamorphic assemblage may cool down perhaps even to ordinary temperature as a perfectly stable mineral assemblage. For their preservation there is no requirement of a rapid cooling or quenching of those minerals and mineral assemblages which nevertheless do require a high temperature for their production *by metamorphism of carbonate rocks*. The assemblages formed at high temperatures may and frequently do suffer changes at lower temperatures, but these seem to be connected with high concentrations of water and low CO_2 concentrations. Under such conditions have apparently been formed the remarkable assemblages of unusual minerals at Crestmore, California, at Velardena, Mexico, and at Scawt Hill, Ireland, silicates with hydroxyl or fluorine, such as foshagite and custerite, and the silicate-carbonates (other than spurrite), scawtite, and tilleyite. Of course, silicates with hydroxyl or fluorine, such as vesuvianite or chondrodite, may be formed in the rising-temperature cycle that has been discussed at some length, but their systematic treatment is beyond the scope of this study.

There is here no intention of suggesting that assemblages of our simple system, formed at high temperatures, are never transformed at low temperatures to the appropriate simple assemblage. A carbonate rock that has been changed entirely to lime-magnesian silicates may revert to an assemblage of calcite, dolomite, and quartz. The only requisite for reversal is that CO_2 be supplied at adequate pressure for the prevailing temperature (or solutions with adequate partial pressure of CO_2). For the accomplishment of such a cycle of metamorphism it is perhaps necessary to suppose that the carbonate rock first was exposed to the high temperature of an inner zone of the metamorphic aureole of an intrusive, suffered appropriate change to a high-temperature assemblage, and cooled down without further

change. Then at some later time the metamorphic rock found itself in a low-temperature zone of the metamorphic aureole of a later intrusive which drove into it CO_2 at an adequate pressure to cause reversal of the reaction, the CO_2 being driven off from carbonate rocks, which by reason of their position had escaped significant metamorphism by the first intrusive. It is not difficult to picture an arrangement of two intrusives of different age that would render possible such a cycle of metamorphism in a rock mass appropriately placed. The picture has in itself no great significance, but it suggests a possible solution of a puzzling problem in geology, in particular that aspect of the picture which provides for a source of great quantities of CO_2. Especially in pre-Cambrian terranes there are colossal volumes of intermediate and basic igneous rocks, largely volcanics, that have been converted into carbonates with chlorite, albite, and minor amounts of other minerals. The original igneous rocks were principally plagioclase and pyroxene, a high-temperature assemblage, more complex chemically than the high-temperature assemblages of our simple system, but, like them, they would be unstable at low temperatures in the presence of CO_2 of adequate concentration (pressure). If we assume this condition, the formation of carbonates would ensue, and though this is only one of the major reactions involved in the more complex case, a principal problem involved is the source of adequate quantities of CO_2. It is here that we may apply the suggestion arising from the dual metamorphic aureole just discussed. A source of CO_2 for the retrograde metamorphism or katamorphism of the igneous rocks may perhaps be found in the prograde metamorphism of impure carbonate beds in the vicinity of igneous masses intrusive into the complex terrane. Apparently there are always intrusive bodies, and the source of the CO_2 is sometimes sought in the magmas forming these intrusives, but such quantities of CO_2 in magmas are hardly within the bounds of credence. The position is equally untenable that the minute amount of pore solution normally present in a rock could carry enough CO_2 to effect more than negligible changes as the temperature fell to values appropriate to other equilibria. An abundant source of CO_2 is requisite, and the only possible one appears to lie in carbonate beds suffering metamorphism.

THE PRESSURE-TEMPERATURE CURVES

It is perhaps desirable to discuss some of the general relations of the P-T curves of Figure 14. They are curves of univariant equilibrium and, except in some limiting cases, represent equilibrium between five phases in a four-component system. The question naturally arises as to whether any of these curves meet at univariant points. The first four curves are purely schematic and are concerned with equilibria that involve alternately quartz and forsterite. Two adjacent curves could intersect, therefore, only at a point where forsterite and quartz are in equilibrium. There is no temperature, at ordinary pressure, where quartz and forsterite can coexist. They combine to form enstatite, and the volume relations are such as to discourage belief that high pressure would favor formation of forsterite and quartz. It may be concluded, therefore, that none of the first four curves intersects each other at any pressure. The curve *a* will intersect each of the curves *1* and *3* at some point, and each point will be an invariant point (sextuple), but these points will not be discussed in detail. The point of intersection of curve *a* with curve *6* displays the same general relations and is controlled by the same principles and will be chosen for discussion instead. Since curve *6* is concerned with a limiting case of ternary equilibrium in which quartz is one of the phases, the intersection with curve *a* will be an invariant (quintuple) point. At this point five phases are in equilibrium—calcite, wollastonite, α-quartz, β-quartz, and CO_2. From it should emanate five curves of univariant equilibrium between four phases as follows:

d) calcite + wollastonite + α-quartz + β-quartz
e) calcite + CO_2 + α-quartz + β-quartz
f) wollastonite + CO_2 + α-quartz + β-quartz
g) calcite + wollastonite + α-quartz + CO_2
h) calcite + wollastonite + β-quartz + CO_2

Curves *d* and *e* will coincide with each other and with that portion of curve *a* of Figure 14 which lies at lower temperatures than the point of intersection. Curve *f* coincides with that portion of curve *a* which lies at higher temperatures than the point of intersection. Curves *g* and *h* are the two portions of curve *6* of Figure 14, the part which lies

below and the part which lies above the temperature of intersection, respectively. There should indeed be a slight change of slope of curve *6* of Figure 14 at this point of intersection. The five curves about the quintuple point, by reason of the fact that two of the phases, α- and β-quartz, have the same composition,[32] are thus reduced to three, the curve of equilibrium of α- and β-quartz which passes without discontinuity through the point and the two curves that are shown in Figure 14 as the one curve *6*. The point of intersection is nonetheless a quintuple point.

Curve *5* is the dolomite-dissociation curve based on rough determinations by Eitel,[33] and curve *6* is the well-known calculated curve of Goldschmidt.[34] Neither can be regarded as established with sufficient accuracy to warrant insistence on the plotted relations. It has, indeed, already been suggested that they cross; that at low pressures the dolomite dissociation comes at lower temperatures than wollastonite formation, whereas at high pressures the wollastonite equilibrium runs at lower temperatures. The point at which they cross, if there is such a point, may lie at higher pressures than any indicated on Figure 14. In any case, it is to be noted that such a point is of an entirely different nature from those points just discussed and is in no sense a unique equilibrium point. It is merely the point at which the P-T curves of two wholly independent chemical systems happen to cross. They are the projection on the P-T plane of the P-T-X (pressure, temperature, composition) equilibria of two systems having wholly independent compositions. The point at which they might cross has thus no chemical significance any more than has the point where the curve *a* crosses a curve of equilibrium in which quartz has no part.

All the other curves of Figure 14 are purely schematic, except *b* and *c*. The latter is the determined curve of dissociation of calcium carbonate up to the temperature where melting phenomena intervene. In view of the position of this curve it is not surprising that

[32] G. W. Morey and E. D. Williamson, *Jour. Amer. Chem. Soc.*, Vol. XL (1918), pp. 59–84.

[33] W. Eitel, *Neues. Jahrb. f. Min.*, Beilage Band LI (1925), S. 477–93.

[34] It is firmly embedded in the literature that the Goldschmidt calculation gives a pressure of approximately 1 atmosphere at 500° C. As a matter of fact, log p is approximately 1 at 500° C. and the pressure is somewhat more than 12 atmospheres.

calcium carbonate in nature never suffers simple dissociation into lime and CO_2. The curve does suggest, of course, that a block of limestone in a basic lava flow at, say, 1150° C., would be dissociated unless it was immersed to a depth of more than some 200 feet below the surface of the liquid lava. The block would inevitably have suffered additive metamorphism as it was heated up in the magma with the development of various silicates, but, if any calcite survived, it would be dissociated, provided the conditions were those suggested above. Any lime that may have been so formed would be so reactive that it would enter into combination during the cooling and crystallization of the magma, and the evidence that it had ever formed would undoubtedly be lost.

Curve *b* is the inversion curve of wollastonite to pseudowollastonite and is shown as a vertical line because the densities of the two forms are sensibly the same, at least at the ordinary temperature, and pressure would therefore have a negligible effect upon the temperature of transformation. The curve *b* is also intended to indicate the approximate upper limit of temperature of magmas in the accessible part of the earth—a temperature which far exceeds that prevailing during most episodes of metamorphism (or mineral formation of any kind) except perhaps in some examples of pyrometamorphism induced by basic magmas. Here the temperature may have equaled this value or perhaps surpassed it in moderate degree, for lavas may possibly attain somewhat higher temperatures under surface conditions than they ever attain at other levels of the accessible crust.[35] The reasons for taking this temperature as a probable upper limit of temperatures available in the accessible crust are the nonoccurrence of pseudowollastonite in natural rocks and the failure of evidence that wollastonite is ever a pseudomorph after pseudowollastonite.

Curves *7* and *8* are concerned, respectively, with monticellite and with akermanite formation. Akermanite is itself probably unstable at all temperatures of these curves so that curve *8* can be regarded only as a schematic presentation of the relative conditions of formation of melilite, a solid solution containing akermanite. Curve *7*

[35] Bowen, *The Evolution of the Igneous Rocks* (Princeton: Princeton University Press, 1928), p. 184.

represents the coexistence of the five phases—calcite, diopside, forsterite, monticellite, and CO_2—but, since experimental evidence shows that monticellite and diopside do not coexist at high temperatures, the curves *7* and *8* are shown as intersecting at an invariant (sextuple) point where curve *7* ends and curve *7a*, an independent curve with a different slope, begins and runs to higher temperatures, the phases in equilibrium being calcite, forsterite, monticellite, akermanite, and CO_2. The curve *8* would, however, be continuous through the point because both parts of it are nominally concerned with the equilibrium diopside + calcite $\rightleftarrows$ akermanite + CO_2, and the other phases present (monticellite below the invariant point and forsterite above it) have no part in the reaction. This is indeed much ado about a curve and an intersection which probably do not exist as such, akermanite being presumably unstable at these temperatures; but, since the curve is here used to represent the more complex melilite equilibrium, it has been considered desirable to show and discuss this intersection, because it expresses diagrammatically the fact that equilibria involving coexistence of monticellite and diopside occur below a certain temperature, above which they are replaced by equilibria involving coexistence of forsterite and akermanite (melilite).

Curve *9* is concerned with a subsidiary reaction which requires no special discussion. Curve *10* refers to a reaction in the three-component system resulting in the formation of spurrite. Concerning it and the higher temperature curves, it can be said only that they represent the apparent relative positions of these reactions. Spurrite occurs in such a manner as to suggest that it is formed in the ascending cycle in the same general manner as the other minerals of the metamorphic series under discussion and not during retrograde metamorphism as are most of the minerals (probably including the closely related tilleyite) associated with the species formed in the reactions of these higher curves. In 1916 Niggli studied equilibrium in carbonate melts and interpreted his results as indicating that there were certain conditions under which Ca_2SiO_4 and calcite were in equilibrium with each other and CO_2 (about 850° C. and 1 at. CO_2).[36] But spurrite is evidently stable under some conditions, and,

[36] Niggli, *Zeits. f. anorg. Chemie*, Vol. XCVIII (1916), p. 305.

if we accept Niggli's interpretation, it is necessary to conclude that there is a point at which calcite, spurrite, and Ca_2SiO_4 are in equilibrium. This relation would give rise in the ternary system to a quintuple point at which the five phases—wollastonite, calcite, larnite, spurrite, and CO_2—would be in equilibrium. From the quintuple point would emanate the five curves of univariant equilibrium concerned with the five assemblages of four phases each, as follows:

1. Wollastonite, calcite, larnite, spurrite
2. Wollastonite, calcite, larnite, CO_2
3. Wollastonite, calcite, spurrite, CO_2
4. Wollastonite, larnite, spurrite, CO_2
5. Calcite, larnite, spurrite, CO_2

Two arrangements of these curves which permit the coexistence of larnite (the mineral name is here used loosely to indicate the compound Ca_2SiO_4 in any form) and calcite at atmospheric pressure are given in Figure 15, *a* and *b*, each curve being numbered to indicate its equilibrium assemblage in accordance with the numbered assemblages above. Curves *1* and *5* actually form one continuous curve which coincides with the curve of binary equilibrium, calcite + larnite $\rightleftarrows$ spurrite, and is nearly vertical. But if Figure 15, *a*, represented the facts, then it would not have been possible to prepare spurrite (or a crystalline substance having the same composition) from its components at 350° C., which was done by Shepherd,[37] since the curve *1*, *5* would represent the minimum temperatures (nearly constant at all pressures) of existence of spurrite. And if Figure 15, *b*, were valid, then it would not have been possible to make spurrite (or an isomer) at 1380°, as was done by Eitel,[38] for the curve *1*, *5* would indicate the maximum temperature of existence of spurrite. Experimental evidence is thus apparently contradictory. At

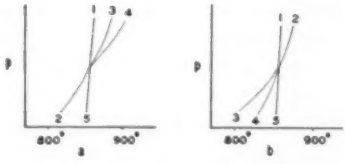

FIG. 15.—Pressure-temperature curves about a hypothetical quintuple point—calcite, spurrite, wollastonite, larnite, CO_2.

[37] In F. E. Wright, *Amer. Jour. Sci.*, Vol. XXVI (1908), p. 551.

[38] *Neues Jahrb. f. Min.*, Beilage Band XLVIII (1923), S. 63.

present it seems best to accept the evidence that spurrite, or an isomer, is stable throughout the whole temperature range of our diagram and that under no conditions is larnite or some form of Ca_2SiO_4 in equilibrium with calcite. This is accomplished in the diagram by drawing an independent curve of the spurrite-wollastonite-calcite equilibrium which never intersects any curve involving larnite. Revision may be necessary with increased knowledge.

On the other curves of the diagram little comment is needed. With advancing knowledge the relations suggested may require notable revision. This would be especially true if investigation should prove that merwinite and larnite are not different phases but different concentrations of the same phase, a possibility that is suggested by the remarkable similarity of their properties. The similarity is, however, no greater than that displayed, say, by monticellite and forsterite, and these are undoubtedly distinct phases, so that the suggested drastic modification of this part of the equilibrium diagram may not be necessary.

OF FACIES

The curves of Figure 14 indicate clearly that, aside from certain possible complications already fully discussed, the formation of any given metamorphic mineral of the series will require a higher temperature if the pressure be low than if the pressure be high. The formation of a certain mineral, such as monticellite, for example, might be taken as indicative of the attainment of a certain grade of metamorphism, or the rock containing it might be described as belonging to a monticellite facies, if we adopt the language of the facies classification. When reactions such as those here considered are involved, it is plain that the development of a certain facies cannot be taken as indicating a definite set of conditions. At a low pressure a monticellite facies would be developed at a comparatively low temperature; at a higher pressure it would be developed only at a higher temperature, and no definite statement about either one of these conditions could be made without rather definite knowledge of the other. The concept of facies as thus used may therefore be a rather indefinite one as far as assignment of conditions of formation is concerned. It is often said, too, that two kinds of rocks are isofacial

with each other, and in so far as they are found side by side and evidently formed under identical conditions they are, indeed, for that occurrence isofacial. The term is, as so used, simply a truism, and any attempt to extend the concept of isofaciality must be carried out with caution. We cannot, for example, make the assumption that, because the materials of these two rocks formed certain assemblages of minerals under these conditions, therefore when the one assemblage is found elsewhere the other assemblage is to be expected there also, if any rock material of the same bulk composition as this second assemblage exists there. On the contrary, the bulk composition which had given the second assemblage might now be found as a totally different assemblage. This is a necessary consequence of the possible difference in the forms of the P-T curves of the reactions the two different materials are capable of experiencing, a fact that is illustrated in highly simplified form in the relation between curve *6* and curve *a* of Figure 14. These two curves intersect at about 100 atmospheres, and this fact indicates that below 100 atmospheres a quartzite made up entirely of α-quartz could form at the same temperature as a wollastonite marble. The two rocks could thus form side by side; in other words, they would be isofacial. But above 100 atmospheres a quartzite composed of α-quartz could form at the same temperature as a quartz marble, and these two would be isofacial. It is plain, therefore, that we cannot make any such statement as "wollastonite marble is isofacial with an α-quartz quartzite," and in general we must be very careful about stating that any rock is isofacial with another rock.

This limitation upon the use of such terms arises from the fact that the P-T curves of different equilibria have different slopes, a relation which is not, however, a disadvantage but is rather a distinct advantage in attacking questions of petrogenesis. In addition to the curves *a* and *b* of Figure 14, which refer to equilibria between solids only, we may eventually be able to determine a large number of such curves, perhaps for more complex equilibria, but still for equilibria between solids only. These curves will be nearly vertical and thus will cut across the curves involving a gas equilibrium. Of these latter it may eventually be possible to add many more, depicting the dissociation of hydrates, sulphides, oxides, and other

compounds. The intersecting curves of the two classes will thus cut the general P-T diagram up into a grid which we may call a petrogenetic grid. With the necessary data determined by experiment we might be able to locate very closely on the grid both the temperature and the pressure of formation of those rocks and mineral deposits of any terrane that were formed at a definite stage of its history, provided always that a sufficient variety of composition of materials occurred in the terrane to permit adequate cross reference. The determinations necessary for the production of such a grid constitute a task of colossal magnitude, but the data will be gradually acquired, and we shall thus slowly proceed toward an adequate knowledge of the conditions of formation of rocks and mineral deposits. It was probably with considerations of this kind in mind that Eskola proposed his concept of the facies. Undue emphasis upon either pressure or temperature is avoided, as is especially any assumption regarding concomitant variation of temperature with pressure (depth). Rather is it necessary to be able to view mineral formation as affected by pressures and temperatures that may vary for the most part quite independently of each other, though in the depths, where pressures are high, there can, of course, be none but comparatively high temperatures.

GEOMORPHIC PROBLEMS AND GLACIAL GEOLOGY OF THE YELLOWSTONE VALLEY, PARK COUNTY, MONTANA

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ABSTRACT

The Yellowstone Valley, between the Gallatin and Beartooth ranges in southern Montana, is the easternmost of the Tertiary basins characteristic of the Northern Rockies. It is a structural basin bordered by a fault along its eastern margin and is partially filled by Upper Miocene–Lower Pliocene beds. Erosion surfaces in adjoining mountains and along the valley are described and correlated. Obscure phases of the Tertiary and early Quaternary history are pointed out.

Two substages of the Wisconsin glaciation are considered, and the possibility of pre-Wisconsin glaciation is recognized.

INTRODUCTION

The valley of the Yellowstone River south of Livingston, Montana, is the easternmost of the Tertiary basins so characteristic of the Northern Rockies, and its eastern border forms an appropriate boundary between that physiographic province and the Middle Rockies. The valley is severely enclosed by mountains and terminated at either end by youthful canyons cut in bedrock. The relatively flat valley floor is 35 miles long, 3–6 miles wide, and has an elevation of 4,600–5,600 feet. On the east the bold western front of the Beartooth Range rises over 5,000 feet above the valley (Mount Cowen, 11,190 feet); to the west the more gradual slopes of the Gallatin Range ascend to an irregular crest line whose higher portions are slightly more than 10,000 feet in elevation. Yankee Jim Canyon at the south end of the basin is an impressive gorge cut in pre-Cambrian crystalline rocks, whereas the Lower Canyon forming the gateway to the plains on the north has been eroded in an overthrust sheet of Paleozoic sediments (Figs. 1 and 2).

Previous geological investigations within the area include the work of Iddings and Weed,[1] who mapped the Livingston quadrangle

[1] J. P. Iddings and W. H. Weed, "Livingston Folio, Montana," *U.S. Geol. Surv. Geol. Atlas* (1894), Folio 1.

and outlined the major geological relations; glacial studies by Weed,[2] and more recent detailed mapping of structures by Lammers, Skeels, and Wilson.[3] Weed's report is of special significance in connection with the present paper and represents an important pioneer study of glacial features in the Rocky Mountains.

GEOLOGIC SETTING

STRUCTURAL RELATIONS

In its relations to adjoining provinces the valley is an intermediate area exhibiting features common to the Northern and Middle Rock-

FIG. 1.—View across Yellowstone Valley from near Stricklin Creek, looking eastward toward Emigrant Peak (10,960 feet) in the Beartooth Range. The topography in the foreground is the result of erosion and irregular deposition of drift by the Yellowstone Glacier; the floor of the valley is largely ground moraine. Evidence of faulting along the front of the Beartooth Range is shown by a linear basal scarp and by truncation of ridges.

ies and to the Yellowstone Plateau. Although included within the Northern Rockies by reason of its fill of Tertiary sediments, the extensive area of volcanic eruptives in the Gallatin Range and in

[2] W. H. Weed, "The Glaciation of the Yellowstone Valley North of the Park," *U.S. Geol. Surv. Bull. 104* (1893).

[3] Edward C. H. Lammers, "Structural Geology of the Livingston Peak Area, Montana," *Jour. Geol.*, Vol. XLV (1937), pp. 268–95; D. C. Skeels, "Structural Geology of the Trail Creek–Canyon Mountain Area, Montana," *Jour. Geol.*, Vol. XLVII (1939), pp. 816–40; J. T. Wilson, "Mill Creek–Stillwater Area, Montana" (unpublished MS).

the southern part of the valley serve to link it with the Yellowstone Park region. Structurally related to the Middle Rockies, it occupies a downfaulted portion of the Beartooth axis of uplift.

At the south end of the Bridger Range (Fig. 2) the north-south-trending ranges of the Northern Rockies lose their identity and merge with east-west structures representing the westward continuation of Beartooth lines of deformation. In the vicinity of Living-

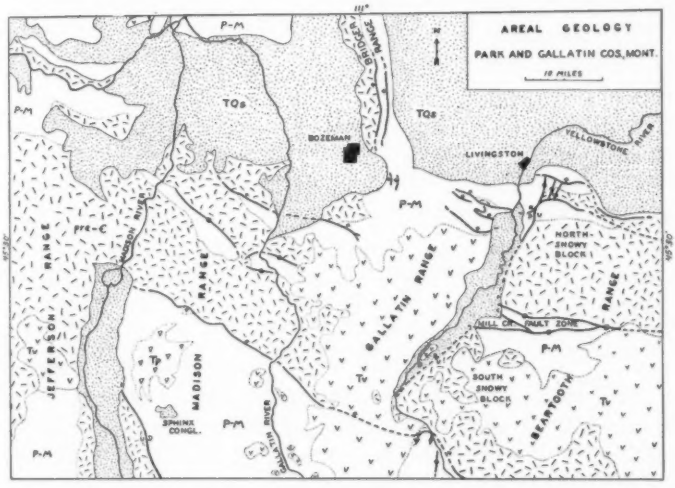

FIG. 2.—Generalized geologic map of parts of Park and Gallatin counties, Montana. Faults are shown by heavy solid and dashed lines; thrust faults have dip arrows, essentially vertical faults are circled, and upthrow and downthrow is shown for normal faults. *Pre-C*, pre-Cambrian crystalline rocks; *P-M*, Paleozoic and Mesozoic sedimentary rocks; *Tp*, Tertiary intrusive porphyries; *Tv*, Tertiary volcanic eruptives, largely basic breccia; *TQs*, Tertiary sediments, Quaternary glacial drift, and alluvium. (Based on the Livingston and Three Forks folios and maps by Lammers, Skeels, and Wilson.)

ston this zone of movement is characterized by a series of north-dipping, low-angle overthrusts. The North and South Snowy blocks, forming the western third of the Beartooth Range, are largely the result of vertical uplift. Both of these blocks have been tilted to the north and are separated by an east-west zone of high-angle faulting along Mill Creek (Fig. 2). The southern border of the South Snowy block is marked by the Gardiner thrust fault

which dips northward under the range.[4] To the west these structures are concealed by the thick accumulation of volcanic eruptives forming the Gallatin Range, although they reappear along the west side of the range and continue as the broad crystalline axis of the Madison Range. The Gardiner fault is doubtless continuous with a similar thrust which appears near the head of Porcupine Creek, and the Mill Creek fault zone may be correlated with high-angle faults along Squaw Creek and Cherry Creek (Fig. 2).[5]

The mountainous aspect of the region is due not to the development of these structures during the Laramide revolution but to subsequent differential movements which did not affect all earlier structures uniformly. In general, accordance of structure with present topography is characteristic of the ranges to the south and east, whereas the mountains of western Montana are seldom linear or in harmony with Laramide tectonic trends. The Bridger, Gallatin, Madison, and Jefferson ranges in the adjoining region to the west constitute examples of mountains in which the summit areas are "off structure" (see Fig. 2).

TERTIARY BASINS OF SOUTHWESTERN MONTANA

The Tertiary basins, which outline the mountain units of western Montana, range in elevation from 3,000 to 5,500 feet and are surrounded by uplands 6,500–11,000 feet high, although the average height would be less than 8,000 feet. These valleys are well known as the result of studies by Pardee, Atwood, Perry, and others,[6] and

[4] W. T. Thom, Jr., O. T. Jones, and R. T. Chamberlin, "Morphology of the Beartooth Uplift, Montana and Wyoming" (unpublished MS); C. W. Wilson, Jr., "Geology of the Thrust Fault near Gardiner, Montana," *Jour. Geol.*, Vol. XLII (1934), pp. 649–63.

[5] A. C. Peale, "Three Forks Folio, Montana," *U.S. Geol. Surv. Geol. Atlas* (1896), Folio 24.

[6] J. T. Pardee, "Coal in the Tertiary Lake Beds of Southwestern Montana," *Contributions to Economic Geology, 1911, U.S. Geol. Surv. Bull. 531* (1913), pp. 229–44; W. W. Atwood, "The Physiographic Conditions at Butte, Montana, and Bingham Canyon, Utah, When the Copper Ores in These Districts Were Enriched," *Econ. Geol.*, Vol. XI (1916), pp. 697–749; Pardee, "Geology and Ground Water Resources of Townsend Valley, Montana," *U.S. Geol. Surv. Water Supply Paper 539* (1925); Eugene S. Perry, "Physiography and Ground Water Supply in the Big Hole Basin, Montana," *Mont. Bur. Mines and Geol. Mem. No. 12* (1934).

the regional aspects of the problem have been summarized by Fenneman[7] and Pardee.[8]

Among the more outstanding features of the basins are: (1) there is present a sedimentary fill of Oligocene–early Pliocene age, Eocene beds being altogether absent; (2) twelve out of seventeen larger valleys show discordance with adjoining structures, and most of these remaining valleys are discordant in part; (3) together the basins form a mature valley system with dominantly south and southeast trends; (4) streams entering and leaving the valleys are superimposed and have eroded youthful canyons in bedrock; (5) Tertiary eruptives are commonly present, and the valley fill contains a high percentage of volcanic ash; (6) the sediments rest unconformably on beds ranging in age from pre-Cambrian to Upper Cretaceous; (7) for the most part the beds are fine grained, in some places containing coal, and in a few instances conglomeratic facies have been reported along the margins of the valleys; and (8) at least ten of the seventeen valleys show evidence of late Tertiary faulting, and in others there has been extensive warping of similar age. Three aspects of the problem of origin present themselves: (1) the relative importance of erosion and diastrophism in outlining the initial basins; (2) the extent of late Tertiary faulting and warping; and (3) the history and integration of pre-Oligocene and present drainage. Intimately related to this problem are two of equal or greater significance; one is the well-known Idaho peneplain problem, and the other concerns the synchronism of Tertiary events in the Northern Rockies, Middle Rockies, and Great Plains.

BOUNDARY STRUCTURE OF YELLOWSTONE VALLEY

Along the east side of the valley the Beartooth massif is terminated abruptly so that the pre-Cambrian rocks forming the crest of the range stand thousands of feet above near-by Paleozoic and Mesozoic beds to the west, which, though largely covered by volcanics, are known to strike into the range. For the North Snowy block it is clear that this relation is due to faulting, because the

[7] Nevin M. Fenneman, *Physiography of the Western United States* (New York: McGraw-Hill Book Co., Inc., 1931), pp. 219–24.

[8] "Geology and Ground Water Resources . . . . ," *op. cit.*

Deep Creek Ridge fault mapped by Lammers[9] can be extended along the foot of the range and is known to dip 80° W. to vertical. Near Elbow Creek (Fig. 3), where the North Snowy block attains its maximum elevation, the throw cannot be less than 5,000 feet. The possibility that this displacement may include movement along a parallel fault in the pre-Cambrian is suggested by a foothills area in crystalline rocks which lies between the mountain front and the projected fault trace beneath the alluvium of the Yellowstone Valley a mile to the west. This foothill area, known to local residents as the "Short Hills," ranges in elevation from 5,800 to 6,200 feet, is best developed between Deep Creek and Strawberry Creek, and is totally absent west of the South Snowy block. Although regarded as an erosion surface, the abrupt termination of the foothills along a linear eastern margin without embayments near canyon mouths is indicative of structural control.

The Mill Creek fault zone, which enters the valley from the east at about its midpoint (Fig. 2), coincides with a re-entrant in the mountain front and a change in its trend from N. 20° E. to N. 50° E. South of this point there is no stratigraphic proof of faulting along the margin of the South Snowy block, yet physiographic criteria here are much clearer than to the north. The major topographic features indicative of faulting are the linear scarp near the foot of the range, the complete absence of foothills, truncated ridges, the abruptness and continuity of the mountain front, and the hanging valleys south of the Six Mile Creek (Fig. 1). Other lines of evidence supporting this conclusion are the alignment of porphyry intrusives and hot springs along the base of the range, the marked difference in elevation of the early basic breccias in the Beartooth Range and the area to the west (Fig. 4), and the recent fault scarp cutting an alluvial fan just north of the mouth of Yankee Jim Canyon.[10] Porphyry intrusives are exposed in the vicinity of Chico Hot Springs, along the road near the mouth of Six Mile Creek, and at the edge of the valley east of Duck Lake (Fig. 3). A travertine deposit between Emigrant and Six Mile creeks in the vicinity of the Blakesley

[9] *Op. cit.*, pp. 272–73.

[10] *Guidebook, Bighorn Basin–Yellowstone Valley Tectonics Field Conference, August 3–5, 1937* (Billings, Mont.: W. W. Gail, 1937), p. 16.

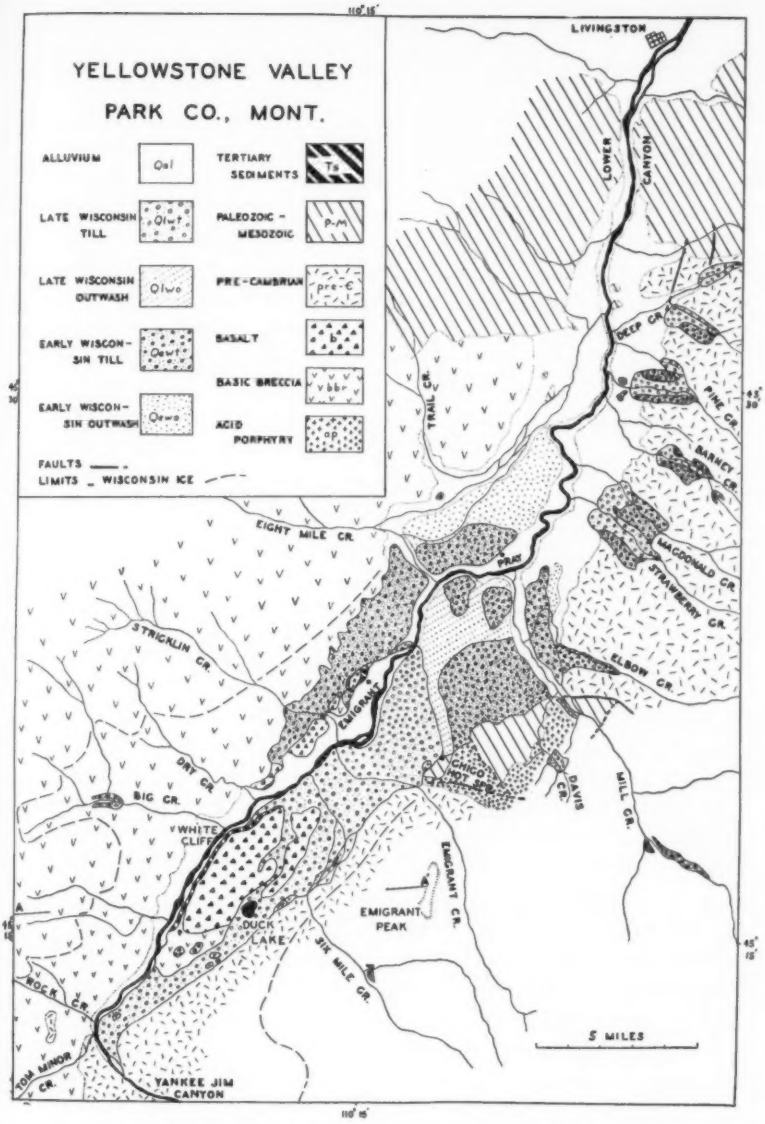

FIG. 3.—Map showing glacial deposits and generalized areal geology. Included under alluvium are terrace gravels, piedmont fan deposits, Wisconsin outwash, and recent flood-plain deposits.

Ranch evidences former hydrothermal activity along the mountain front.

The pre-Cambrian rocks forming the western margin of the Beartooth Range are crystalline foliates, largely schists, which strike parallel to the mountain front and with few exceptions dip to the west at high angles. This suggests control of faulting by structures in the basement complex. Movement along the fault was initiated during an early stage of the Laramide revolution, and perhaps earlier, and at the northern end there appears to have been no subsequent displacement, as the Deep Creek Ridge fault is covered by

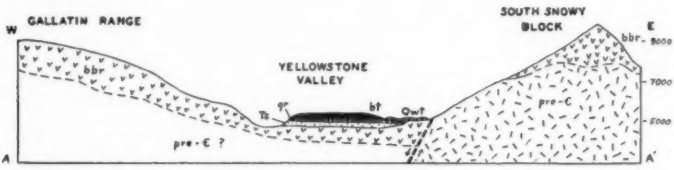

FIG. 4.—Cross section along the line A–A', Fig. 3. *Pre-C*, pre-Cambrian crystalline rocks; *bbr*, basic breccia and intrusive porphyry; *Ts*, Upper Miocene–Lower Pliocene "lake beds"; *gr*, Pliocene or Lower Pleistocene gravels; *bt*, basalt; *Qwt*, Wisconsin till.

the Suce Creek–Window overthrust fault.[11] Farther south more recent movements are indicated by displacement of volcanics and scarps cutting alluvium. Thus it seems probable (1) that differential movements of valley and mountain range during the Cenozoic involved faulting along most of the length of the valley and sharp warping at either end; (2) that the major displacement occurred during the Laramide uplift of the two Snowy Range blocks; and (3) that intermittent movements took place throughout the Cenozoic up to recent time.

The western margin of the valley is irregular, shows no evidence of structural origin, and has had its outlines determined largely by drainage pattern and rock composition. However, the Gallatins cannot be considered wholly mountains of accumulation; instead they represent an elongate, upwarped area of volcanic rocks maturely dissected by streams.

[11] Lammers, *op. cit.*, p. 283.

TERTIARY AND EARLY QUATERNARY FEATURES

VOLCANIC AND SEDIMENTARY RECORD

Early basic breccias.—The early basic breccias of the Yellowstone Park volcanic sequence form the major part of the Gallatin Range, cover extensive areas in the South Snowy block, and are exposed on the floor of Yellowstone Valley south of the mouth of Six Mile Creek (Figs. 3 and 4). They consist largely of breccias and agglomerates but include flows and tuff beds and have been intruded by basic dikes and irregular masses of acid porphyrite. Formerly regarded as Miocene, this sequence is now more generally considered older, probably late Eocene or early Oligocene.[12]

Tertiary "lake beds."—Fine-grained Tertiary sediments, largely of fluvial origin, have long been described as "lake beds" in western Montana. However, the term is no more applicable to these beds than it was to the Tertiary deposits of the Wyoming basin and Great Plains. In the Yellowstone Valley sediments of this type rest unconformably on the early basic breccias and probably underlie a major part of the valley. The beds are for the most part concealed by glacial drift, and exposures are limited to areas in the southern part of the valley which were protected from glacial erosion by basalt flows. Farther north these beds are deeply buried by glacial drift.[13] The most complete section of the "lake beds" in the valley is at "White Cliffs" (Figs. 3 and 5) where 200 feet of buff clays and silts are overlain by 80 feet of gravel capped by basalt. At this point the "lake beds" were tilted about 6° to the northeast and truncated by erosion prior to the deposition of the gravels. The silts and clays are evenly bedded, noncalcareous, and under the micro-

[12] J. T. Rouse, "Genesis and Structural Relationship of the Absaroka Volcanic Rocks, Wyoming," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), pp. 1271–72; John David Love, "Geology along the Southern Margin of the Absaroka Range, Wyoming," *Geol. Soc. Amer. Spec. Paper 20* (1939), p. 85; C. B. Read, "Fossil Floras of Yellowstone National Park," Part I: "Coniferous Woods of Lamar River Flora," *Carnegie Inst. Wash. Pub. 416* (1930), pp. 1–19; Willard H. Parsons, "Volcanic Centers of the Sunlight Area, Park County, Wyoming," *Jour. Geol.*, Vol. XLVII (1937), p. 9.

[13] The well at Chicory, near the mouth of Eight Mile Creek, is reported to have encountered "lake beds" after passing through 400 feet of glacial drift (personal communication, A. W. T. Anderson, Emigrant, Mont.).

scope show a high percentage of volcanic shards together with unweathered grains of biotite, amphibole, quartz, and some feldspar. Silicified remains of various vertebrate animals have been collected here and at an exposure along the highway 3 miles to the north (Fig. 3).[14] A more tuffaceous facies of the "lake beds" occurs beneath 40 feet of gravel capped by basalt about ½ mile south of Emigrant (Fig. 3). Fine-grained deposits are here interbedded with discontinuous zones of rubble derived from the basic breccias to the west. Foreset beds dipping to the east suggest fluvial deposition by

FIG. 5.—"White Cliffs" along the Yellowstone River 7 miles south of Emigrant, Montana. Light-colored "lake beds" (*Ts*) are overlain unconformably by poorly cemented gravels (*gr*). The exposure is capped by basalt flows (*bt*).

streams from uplands to the west. The silts are slightly calcareous and contain abundant volcanic shards and small cinders. No vertebrate remains have been found at this locality. A thickness of about 300 feet of silts and clays has been reported from the well at the Northern Pacific Railway quarry 5 miles south of Emigrant.[15]

[14] The most complete collection of vertebrates from the "lake beds" in Yellowstone Valley belongs to Dr. C. E. Marshall, an enthusiastic amateur paleontologist, of Livingston, Mont.

[15] The well is reported to have passed through 42 feet of glacial drift, about 300 feet of "lake beds," and 62 feet of basalt (?) underlain by water-bearing gravels (Jerry Fogerland, personal communication). The gravels and basalt noted here are older than those previously referred to and are not known to outcrop at the surface.

The deposits in Yellowstone Valley contain vertebrate fossils of probable late Miocene–early Pliocene age[16] and are to be correlated with the upper part of the Bozeman beds of the Three Forks and Madison valleys.

Gravels and overlying basalt.—The stream gravels occurring between the basalt flows and "lake beds" are included with the "Tertiary sediments" shown in Figure 3. They are exposed at "White Cliffs," at the Northern Pacific Railway quarry 5 miles south of Emigrant, and along the bluffs west of the Yellowstone River near Emigrant. At "White Cliffs" the thickness of the deposit is about 80 feet, and ½ mile south of Emigrant the thickness is about 40 feet. The gravels are composed of well-rounded cobbles which have an average diameter of 4 inches and are loosely cemented by a sand matrix. The lithologic composition is shown in Table 1. Poorly defined imbrication suggests deposition by a north-flowing stream.

The basalts forming the low mesas and benches in the southern part of the valley represent remnants of flows which once extended down the valley at least as far as Eight Mile Creek where small exposures have been noted (Fig 3). The rock is a dark-gray, olivine basalt which occurs as horizontal flows separated by scoriaceous zones. Two distinct flows, each about 15 feet thick, are well shown where the rock is being quarried 5 miles south of Emigrant. The flows rest unconformably upon the Tertiary gravels, "lake beds," and early basic breccias. Southwest of Duck Lake the flows spread over and around hills of breccia.

Since the gravels overlie beds which are late Miocene or early Pliocene and show no evidence of glacial derivation, their age is either Pliocene or early Pleistocene. Correlation with the basalts and gravels in the vicinity of Tower Falls in Yellowstone Park is uncertain, although Howard has pointed out that the rarity of rhyolite pebbles in the gravels at "White Cliffs" suggests a pre-rhyolite age and equivalence with some of the older Canyon basalts.[17] If due

[16] Childs Frick and Glenn L. Jepson, personal communication. Merycodontine ramal fragments, *Cosoryx* var. (?), from the Marshall collection are noted by Frick ("Horned Ruminants of North America," *Bull. Amer. Mus. Nat. Hist.*, Vol. LXIX [1937], pp. 319, 346, 411).

[17] Arthur David Howard, "History of the Grand Canyon of the Yellowstone," *Geol. Soc. Amer. Spec. Paper 6* (1937), p. 64.

allowance is made for the opportunity provided for loading of crystalline rocks, the pebble counts from the two areas show considerable similarity (see Table 1). At Tower Falls fragmentary vertebrate remains were collected years ago and identified by O. C. Marsh as belonging to a Pliocene horse.[18]

TABLE 1

COMPOSITION OF GRAVELS BELOW BASALT

Rock Type	Per Cent				
	1	2	3	4	5
Basalt	48	63	46	.....	.....
Basic breccia	4	1	0	.....	.....
Chalcedony and jasper	2	1	0	.....	.....
Felsite and felsite porphyry (largely andesite)	13	16	21	.....	.....
Total volcanics	67	81	67	82	79
Granite	16	5	9	0	0
Gneiss	5	4	13	0	0
Schist	0	0	0	1	0
Basic plutonics	5	0	2	0	0
Total crystallines	26	9	24	1	0
Quartzite	7	10	9	17	21
Total	100	100	100	100	100

1. One-half mile south of Emigrant, Montana.

2. Northern Pacific quarry, 5 miles south of Emigrant, Montana.

3. "White Cliffs," 7 miles south of Emigrant, Montana.

4. Gravels under Overhanging Cliff basalt (Howard, *op. cit.*, p. 40).

5. Gravels below lower basalt on the northeast side of the canyon opposite Tower Creek (*ibid.*, p. 53).

EROSION SURFACES

Pre-Oligocene surface.—Underlying the "lake beds" of adjoining areas is an extensive erosion surface which truncates beds ranging in age from pre-Cambrian to Fort Union (Livingston formation). These relations are well shown in the Livingston, Three Forks, and

[18] Arnold Hague, "Yellowstone National Park Folio, Wyoming," *U.S. Geol. Surv. Geol. Atlas* (1896), Folio 30, p. 3.

Little Belt folios.[19] The original extent and character of the surface is difficult to determine because of subsequent differential uplifts of mountains and basins. The fine-grained character of the Tertiary "lake beds," as compared with present stream loads, indicates much lower local relief than at present. For the most part this surface has been regarded as Eocene in age and correlated with the summit surfaces of adjoining mountains,[20] although the questions raised by the Idaho peneplain controversy cannot be considered settled and the summit surfaces in the mountains may well be much younger. It has been suggested by Bevan[21] that the "summit peneplain" of the Beartooth Range may be equivalent to this surface.

Upland surface.—In the Beartooth Range the upland surface is well developed on the crystalline rocks of the North Snowy block.[22] Here undissected remnants give rise to the East and West Boulder plateaus, which range in elevation from 9,000 feet to almost 11,000 feet. The narrow, even-crested divide between the West Boulder River and Yellowstone Valley represents the westward continuation of the surface, and similar features are found on the South Snowy block between the headwaters of Hell Roaring Creek and the Middle Fork of Mill Creek. That this does not represent the exhumed pre-Cambrian peneplain, as suggested by Hughes,[23] is evidenced by the southward continuation of the surface across the Mill Creek fault zone and onto the Tertiary volcanics of the South Snowy block without change in elevation. By Bevan[24] the Beartooth upland was interpreted in terms of a summit surface of Oligocene age and a subsummit surface of Pliocene age, the latter being represented by the Boulder plateaus. Later studies by Sharp[25] have led to the belief

[19] Iddings and Weed, *op. cit.;* Peale, *op. cit.;* Weed, "Little Belt Mountains Folio, Montana," *U.S. Geol. Surv. Geol. Atlas* (1899), Folio 56.

[20] Atwood, *op. cit.*, p. 708; Pardee, "Geology and Ground Water Resources . . . . ," pp. 38–43.

[21] Arthur Bevan, "Rocky Mountain Peneplains Northeast of Yellowstone Park," *Jour. Geol.*, Vol. XXXIII (1925), pp. 575–76.

[22] Shown on the Livingston, Montana, topographic sheet.

[23] R. V. Hughes, "Geology of the Beartooth Mountain Front," *Proc. Nat. Acad. Sci.*, Vol. XIX (1933), pp. 239–53.

[24] *Op. cit.*, pp. 568 and 578–87.

[25] Henry S. Sharp, "The Upland of the Beartooth Mountains, Montana," *Geol. Soc. Amer. Proc. 1937* (1938), p. 113.

that the upland exhibits one unit surface—except for restricted resurrected areas—of late Tertiary, probable Pliocene, age.

At the north end of the Gallatin Range a broad, flat-topped divide (9,200–9,600 ft. elevation), extending north from the head of Eight Mile Creek, forms a summit surface similar to that of the Beartooth Range but of lower average elevation.[26]

Flaxville Plain or Terrace No. 1.—No clear-cut surfaces representing the Flaxville Plain are present in the area, although extensive remnants along the southwest margin of the Crazy Mountains northeast of Clyde Park (Fig. 6) and in the vicinity of Big Timber have been mapped by Alden.[27] In the vicinity of Livingston it is estimated that the Lower Canyon had been eroded to a depth of 5,500 feet by Flaxville time.[28] If this elevation, based on projection of profiles, is accepted, the partially dissected, mature surfaces found at higher elevations at the Lower Canyon and in the "Short Hills" along the east side of the valley will have to be considered older, and intermediate in age between the upland surface and the Flaxville Plain. The Canyon Plateau surface (Fig. 6) truncates the deformed Paleozoic beds at elevations of 6,200–6,400 feet and evidences a mature-valley stage in the history of the Yellowstone River. When viewed from a distance, the profile of the old valley is clearly revealed, and it is seen that the lowest part is next to the Beartooth front over a mile east of the present canyon. The "Short Hills" surface has been partially glaciated and extensively eroded so that its elevations range from 5,800 to 6,200 feet. Parts of the surface show bedrock control of topography with higher ridges held up by quartzites and quartz schists; mantle rock covers the slopes and appears to be quite deep on the flatter portions. By reason of its position within the valley of a master, through-flowing stream, the surface is interpreted as a maturely dissected, old valley floor formed by lateral planation. Lower than the Canyon Plateau, it is still

[26] The surface is shown on the Livingston topographic sheet and was briefly mentioned by Emmanuel de Martonne, "Le Parc national du Yellowstone: Equisse morphologique," *Amer. Geog. Soc. Mem. Vol., 1912* (1915), p. 242.

[27] Willian C. Alden, "Physiography and Glacial Geology of Eastern Montana and Adjacent Areas," *U.S. Geol. Surv. Prof. Paper 174* (1932), p. 25.

[28] *Ibid.*

considerably above the projected Flaxville Plain and will have to be considered somewhat older.

Gravels on the Flaxville Plain have been assigned a late Miocene–early Pliocene age on the basis of vertebrate fossils, although the

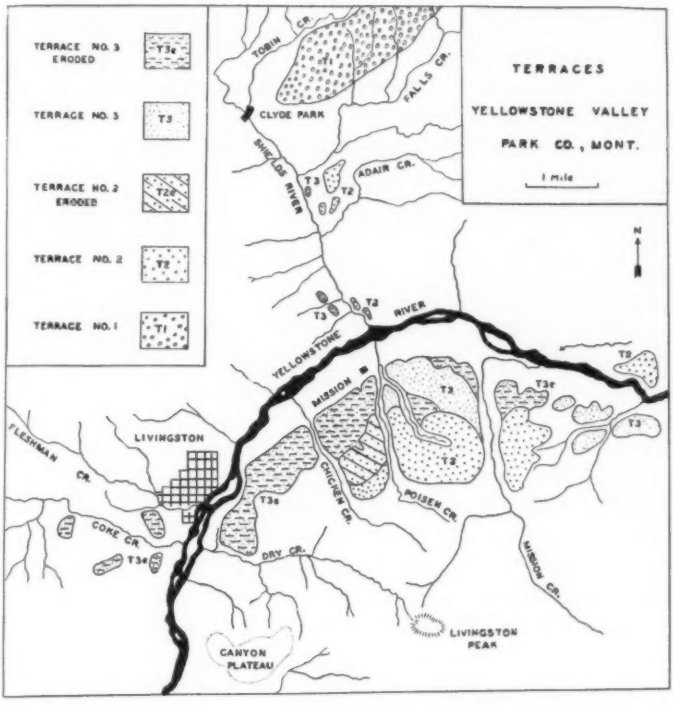

FIG. 6.—Terraces along the Yellowstone Valley, Park County, Montana

associated remains of a Pleistocene camel have led to the suggestion that deposition may have continued into early Pleistocene time.[29] But there is also vertebrate evidence to support a late Miocene–early Pliocene age for the "lake beds" in Yellowstone Valley, and it is doubtful whether both could have been deposited contemporaneously in the same region. The lithology and structural relations

[29] *Ibid.*, pp. 12–14.

of the Flaxville gravel and "lake beds" point to radically different conditions of origin. Although the Flaxville Plain is not known to truncate the "lake beds" anywhere within the area, its projection would rise well above the "lake beds" in Yellowstone Valley. Because of these relations and the uncertainties attending the dating of the Flaxville Plain, a younger age, late Pliocene–early Pleistocene, is favored for that surface.

Terrace No. 2.—The distribution of Terrace No. 2 in the vicinity of Livingston is shown by Figure 6, in which the correlation of surfaces is based largely on Alden's map.[30] In this area Terrace No. 2 is represented by flat remnants which have been but slightly lowered by slope wash (*T2*, Fig. 6) and by irregular surfaces at lower elevations (*T2e*, Fig. 6). The latter represent transitional slopes and levels at various elevations due to downward and lateral cutting by tributary streams in the gravels deposited by the Yellowstone to form the original surface of the terrace. Uneroded sections of the terrace occur 260–420 feet above the river at elevations of 4,700–4,890 feet; the eroded levels are as much as 80 feet lower. The terraces show more relief than is apparent from a distance; streams have eroded broad shallow valleys in the gravels, and there is a general upward slope toward interstream areas. Folded beds belonging to the Livingston formation (Fort Union) have been truncated, and undissected portions of the terraces are overlain by at least 50 feet of gravel. Along the Yellowstone River the gravels contain abundant volcanic materials and clearly show that the terraces were formed by lateral planation by the master-stream. There is no difficulty in differentiating recent alluvial-fan deposits from the underlying terrace gravels.

In the mountains surrounding Yellowstone Valley a broad-valley stage may be recognized which Alden[31] has correlated with No. 2 bench. Along Big Creek in the Gallatin Range the old valley floor is well preserved as a bench about 600 feet above the present stream at elevations of 5,600 to almost 7,000 feet. Although greatly modified by glaciation, a similar surface can be identified along Dry Creek (Fig. 7), Rock Creek, and Point of Rocks Creek, and the broad valley and sag at the head of Trail Creek may date from a similar pe-

[30] *Ibid.*, Pl. I. [31] *Ibid.*, pp. 51–52.

riod. The broad valleys are not so clearly shown in the Beartooth Range but were noted along the south side of the Middle Fork of Mill Creek and along Emigrant Creek.

Terrace No. 2 is regarded as pre-Kansan, possibly pre-Nebraskan, in age,[32] and its general features are those of the Black Rock surface of western Wyoming.

Terrace No. 3.—Below Livingston eroded and uneroded parts of Terrace No. 3 are shown in Figure 6 and in Figure 3; areas mapped as "alluvium" north of Pray, except for recent flood plains, represent essentially this surface. In the former area the terrace is repre-

FIG. 7.—View east across Yellowstone Valley showing glaciated canyons and early Wisconsin lateral moraines (*lm*) of South Deep Creek (*left*) and Pine Creek (*right*). The prominent ridge at the mouth of Pine Creek is the *north* lateral moraine, and the valley cutting it off from the mountain front is a wind gap marking an interglacial course. At present Pine Creek flows behind this moraine, and the older valley is occupied by a short tributary.

sented by two parts, 50–70 feet apart (*T3* and *T3e*). These levels are 160–230 feet above the river at elevations of 4,390–4,530 feet. Truncation of steeply dipping Livingston beds is well shown along the road east of the Yellowstone River just below Livingston. Southwest of the city, terrace remnants rise to elevations of almost 5,000 feet. Except where recent fans of debris from the vicinity of Livingston Peak (Fig. 6) have been spread out on the terraces, the composition of the gravels indicates deposition by the Yellowstone River.

South of Livingston, where Terrace No. 3 has been modified by glaciation, its relation to the glacial deposits has been discussed by Alden.[33] Along the margin of the North Snowy block the terrace

[32] *Ibid.*, pp. 31–32.

[33] *Ibid.*, pp. 62 and 123.

merges with piedmont deposits which have been superimposed upon the bench. Except at the south end of the valley, the Yellowstone is eroding a fill of alluvial material. Within the glaciated portion of the valley the bench has been entirely obscured, and Alden's suggestion[34] that the gravels underlying the basalt may have been deposited during this stage is improbable, as these gravels are considered preglacial.

The terrace bears the same relation to glacial deposits as the Circle terrace of western Wyoming and was completed prior to the advance of the earliest Wisconsin (Bull Lake) glaciers.

SUMMARY OF EVENTS

Any attempt to outline the major events in the geomorphic history of the area and bring them into harmony with features in adjoining regions is attended by numerous difficulties. These difficulties are in part due to limitations in data available within the area, but more largely to inconsistencies presented by earlier studies and the general need of further regional work.

Among the uncertainties to be recognized in connection with local history are: (1) the age of the basalt and underlying gravel at "White Cliffs";[35] (2) the relation of Yellowstone Valley to adjoining basins prior to and during deposition of the "lake beds"; and (3) the time of canyon-cutting and establishment of present drainage. Consideration of the regional aspects of the problem meets with the following difficulties: (1) indication of contemporaneity of the Bozeman beds and Flaxville gravels by vertebrate remains (see p. 289); (2) reconciliation of Alden's conception of progressive denudation in the Great Plains since the Oligocence with the presence of "lake beds" of the same age at low elevations throughout western Montana; and (3) uncertain age or ages of upland surfaces.

In the light of existing evidence certain tentative conclusions of both local and regional import seem justified: (1) important dif-

[34] *Ibid.*, p. 62.

[35] As noted on p. 285, there is evidence that both are older than the plateau rhyolite of Yellowstone Park, and Howard has considered probable equivalents as Pliocene. Alden (*op. cit.*, p. 52), on the other hand, has regarded correlative basalts near Jardine and Gardiner as resting on No. 2 bench. This would relegate both basalt and rhyolite to the Middle Pleistocene.

ferential movements of mountains and basins were recurrent throughout the Tertiary; (2) these movements followed structural trends more often in the Middle Rockies than in the Northern Rockies; (3) regional drainage was established at a time when the volcanic

TABLE 2

Epochs	Yellowstone Valley (present paper)	Yellowstone Park (Howard)	Eastern Montana (Alden)	Western Montana (Atwood)
Pleistocene	Late Wisconsin drift Erosion Early Wisconsin drift Terrace No. 3 Pre-Wisconsin drift (?) Basalt Gravels ("White Cliffs") Terrace No. 2	Hot Spring formations Alluvium Lacustrine formations Glacial drift (Wisconsin)	Wisconsin drift No. 3 bench Iowan-Illinoian drift (?) No. 2 bench Early mountain drift	Wisconsin drift Interglacial interval Pre-Wisconsin drift
Pliocene	Terrace No. 1 (Flaxville) Upland surface Faulting and warping(?) Upper Bozeman formation ("White Cliffs")	Basalts Rhyolite Basalts and gravels Rhyolite Basalt Rhyolite Andesitic flows Late basic breccia	No. 1 bench (Flaxville)	Fourth cycle of erosion Uplift Local erosion plains ("intermediate level")
Miocene	Faulting and warping(?)	Early basalt flows Trachyte Basalts Early basic breccia		Upper Bozeman beds Third cycle of erosion
Oligocene			Cypress Plain (subsummit peneplain)	Second cycle of erosion Lower Bozeman beds Development of intermontane troughs
Eocene	Early basic breccia Pre-Oligocene surface	Early acid breccia ? Pinyon conglomerate	Fort Union	Uplift First cycle of erosion Summit peneplain
Paleocene	Mountain-building Livingston formation	Laramie formation	Lance	Mountain growth

breccias at Yellowstone Park stood higher than adjoining regions, so that the master-streams are radial to that general area; and (4) there has probably been progressive lowering of the Great Plains and Big Horn basin since the development of Terrace No. 1 (Flaxville)—and certainly since the formation of Terrace No. 2.

The views of earlier workers, together with a tentative working hypothesis for the Yellowstone Valley, are shown in Table 2. No attempt is made to consider all alternative hypotheses, and the se-

quence of events proposed is that considered most tenable in the light of existing evidence.

The inception of valley structure dates from the uplift of the North and South Snowy blocks during an early stage of the Laramide revolution, and subsequent development has been largely due to further crustal movements and differential erosion. During the Eocene these structures were worn down to the erosion surface now preserved below the "lake beds" in the basins. Within the mountain certain high-level gravels, such as the Sphinx conglomerate (9,000–10,840 ft. elevation) of the Madison Range[36] (Fig. 2) and the deposit mapped as Canyon conglomerate (8,000–8,900 ft. elevation) in the northwest corner of Yellowstone Park,[37] may represent products of contemporaneous aggradation.

The interval from late Eocene to early Pliocene was marked by intensified volcanic activity, deposition of the Bozeman formation, and by recurrent crustal movements. By Miocene time the Upper Yellowstone drainage had probably developed as a consequent on the basic breccias and on detrital fans sloping away from the Beartooths and Montana front ranges. Whether the "lake beds" in the Yellowstone Valley were ever continuous with similar beds to the west cannot be determined. In attempting to relate them to an extensive Tertiary valley system two outlets suggest themselves: (1) south into the park region and Snake River drainage by way of a channel now buried by volcanics and (2) north through the Trail Creek divide into the Gallatin Valley near Bozeman. The latter would require about 1,500 feet of relative uplift of the Gallatin Range since the early Pliocene. Deformation of this type is more emphatically indicated by the fact that differential movements of some 3,000 feet are needed to account for discrepancies in Oligocene-Pliocene levels in the Northern Rockies and Missouri Plateau. At a time when the plains adjoining the mountain front were aggraded to levels now 6,000–7,000 feet in elevation, "lake beds" found at elevations as low as 4,500 feet in the Yellowstone Valley had been or were being

[36] Peale, *op. cit.*, p. 3.

[37] Arnold Hague *et al.*, "Geology of Yellowstone National Park," *U.S. Geol. Surv. Mono. 32*, Part II (1899), Geology Sheet 10 in accompanying atlas.

deposited. Elsewhere in western Montana sediments of this type are found at elevations as low as 3,000 feet.

The interpretation of late Tertiary–early Pleistocene events is dependent upon the age assigned to the basalt and underlying gravels. If these are referred to the Pliocene, either the terraces of the Great Plains will have to be considered much older than hitherto, or it becomes necessary to postulate an independent stage of denudation and subsequent aggradation unrecorded elsewhere. It is believed that fewer difficulties are presented if the Yellowstone-Lamar valleys are related to the later periods of degradation recognized by other workers in the Great Plains and Wyoming basin provinces.

GLACIAL FEATURES

The glacial features of the Yellowstone Valley, together with those of adjoining areas, have been admirably described in an early paper by Weed,[38] and no attempt will be made to review this material except in so far as it concerns chronologic problems. This work, however, should be referred to for an interesting and remarkably clear description of some of the features noted in the following paragraphs. The general conclusions set forth in the following discussion are in substantial agreement with reconnaissance studies made by Alden.[39]

PRE-WISCONSIN GLACIATION

Evidence of pre-Wisconsin glaciation in Yellowstone Valley is limited to one questionable occurrence of drift at the western edge of the "Short Hills" just north of the north branch of Barney Creek (Fig. 3). At this point a weathered mass of Bighorn dolomite (Ordovician) and smaller fragments of (?) Flathead quartzite (Cambrian) are found resting on crystalline rocks well outside the border of Wisconsin drift and about 800 feet above the Yellowstone River. The nearest exposures of these formations are 8–10 miles away. The blocks of dolomite, with maximum diameters of 4 feet, appear to represent the weathered remains of a large single erratic which would have had a diameter of from 8 to 10 feet. If the deposit is of glacial

[38] "Glaciation of the Yellowstone Valley . . . . ," *op. cit.*

[39] *Op. cit.*, pp. 123–24.

origin, its position and degree of weathering indicate that it is to be correlated with the Buffalo drift of Blackwelder,[40] which is generally referred to the Kansan stage.

EARLY WISCONSIN (BULL LAKE) SUBSTAGE

Yellowstone Valley.—Heading in the northern part of the Absaroka Range and along the south flank of the Beartooth Range, the Yellowstone Glacier[41] descended the valley of the Lamar River and entered the Yellowstone Valley, where, fed by numerous tributaries, it moved northward for 35 miles beyond the park boundary. Its total length, measured from the head of the Lamar Valley, was about 80 miles, and in the vicinity of Yankee Jim Canyon its thickness could not have been less than 3,000 feet. Upon entering the broad valley south of Livingston, the ice thinned rapidly and built its terminal moraine on the valley floor 1 mile north of Pray (Fig. 3). At this point there is no strong morainal embankment, although the topographic contrast between hummocky moraine and outwash plain is marked. East of the river the moraine can readily be followed south to Elbow Creek, whose course was deflected northward by the ice, and beyond to the mouth of Mill Creek. South of this point the border of the drift is marked by low ridges and by the upper limit of scattered erratics on the mountain slope. The outwash plain fronting the moraine is best developed west of the river where it covers an area of several square miles. The extent of this feature, together with the presence of numerous recessional outwash channels and a system of ice-margin channels and terraces along the slope of the Gallatin Range, testify to large amounts of melt water associated with retreat of the ice. This is further supported by the gravelly character of the drift in many areas and by extensive deposits of outwash buried by late Wisconsin till. Gravel deposits of this type are exposed along the main highway east of the river, north of the mouth of Emigrant Creek.

The recessional channels are represented by a countless number of

[40] Eliot Blackwelder, "Post-Cretaceous History of the Mountains of Central Western Wyoming," *Jour. Geol.*, Vol. XIII (1918), pp. 328–33.

[41] This term was first used by Weed, "Glaciation of Yellowstone Valley . . . . ," *op. cit.*, p. 14. Howard (*op. cit.*, p. 85) has referred to the upper part of the same glacier as the Lamar Glacier.

small, short outlets, especially conspicuous near the margins of the drift, and also by several broad channels of greater extent. The latter are exemplified west of the river by dry channels which enter the Yellowstone Valley as hanging valleys about a mile north of Emigrant and by a single channel extending back from the outwash plain northwest of Pray. East of the river similar features were partially developed by streams from the mountains and considerably modified by melt waters of the late Wisconsin glacier. The most prominent of the channels clearly related to the early Wisconsin substage is the broad, abandoned channel which has been completely blocked off and buried by the late Wisconsin moraine in the vicinity of Chico Hot Spring. This channel doubtless carried a large volume of the water concentrated at the eastern margin of the early Wisconsin ice and may have included contemporaneous drainage from both Emigrant and Six Mile creeks. The present channel is filled with late Wisconsin outwash and 3 miles northwest of Chico Hot Spring opens onto a broad outwash plain which stretches north and west to the Yellowstone River, burying a large portion of the early Wisconsin ground moraine (Fig. 3). Smaller channels exist within the ground moraine southwest of Mill Creek.

The Wisconsin age of this drift is evidenced by its topographic position on Terrace No. 3 and by the preservation of constructional forms over wide areas. Since deposition of the drift the Yellowstone River has eroded 100–170 feet below the level of the terminal moraine and outwash plain. The differentiation of drift belonging to two substages is based in part upon the stronger morainal forms of the younger drift, but more largely upon the fact that the late Wisconsin terminal moraine descends into the inner post-early Wisconsin valley of the Yellowstone about 2 miles north of Emigrant[42] (Fig. 3). An age difference is further supported by buried recessional outwash, which may be identified south as far as the mouth of Emigrant Creek, and by a humus zone separating the two drifts at one point. This horizon is exposed along the north bank of Emigrant Creek about a mile above its mouth. That a long time interval was not required for its formation is indicated by the unweathered aspect of constituent minerals when studied under the microscope. The rel-

[42] Alden, *op. cit.*, p. 123.

ative ages of early Wisconsin moraines in the main valley and adjoining mountains is shown at the mouth of Elbow Creek canyon where ground moraine extending out from the canyon is overridden and completely obscured by the outer lateral moraine of the Yellowstone Glacier. However, it is believed that the early Wisconsin drift in the main valley represents essentially the same substage as the typical Bull Lake moraines formed by glaciers in tributary canyons.

Adjoining mountains.—In the North Snowy block all the larger canyons were occupied by early Wisconsin valley glaciers which descended to elevations as low as 5,000 feet and built imposing moraines on the "Short Hills" surface and on No. 3 bench (Figs. 3 and 7). The moraines are now preserved as prominent lateral ridges, which in the case of Strawberry Creek rises 700 feet above younger ground moraine in the central part of the valley. Terminal portions of the moraines have been effaced by subsequent stream erosion and late Wisconsin glaciation, although remnants may be recognized along Pine Creek. The original elevations of the terminal moraines and the height of the latter cannot be used as a measure of interglacial erosion. This is indicated by a decrease in height at the outer extremities of the lateral ridges. Nevertheless, considerable erosion took place during this interval, as the interglacial channel cutting through the north lateral of the Pine Creek moraine is 400 feet below the crest of the moraine and has subsequently been occupied by late Wisconsin ice (Figs. 3 and 7). In the South Snowy block eroded remnants of correlative moraines have been identified along Mill Creek and Six Mile Creek. No early Wisconsin moraines were recognized in the Gallatin Range, although it seems probable that valley glaciers in the larger canyons, Big Creek and Tom Minor Creek, were tributary to the Yellowstone Glacier at this time.

The present topographic aspect and position of the Early Wisconsin moraines, especially along the North Snowy block, are similar to the Bull Lake moraines of western Wyoming.

ICE-MARGIN CHANNELS

Ice-margin channels and terraces were developed along the west slope of the valley during the wane of the early Wisconsin Yellowstone Glacier. They were described in considerable detail by Weed,[43]

[43] "Glaciation of Yellowstone Valley . . . . ," *op. cit.*, pp. 31 and 34.

although he remained in doubt as to their origin. Similar features have been recognized in regions of continental glaciation and along the margins of existing alpine glaciers.[44] Three of the channel types described by Kendall[45] are represented within the area: (1) severed spurs—channels cut through spurs of the main watershed; (2) marginal overflows—shelves along the mountainside representing spillways where ice or till formed one side of the channel; and (3) in-and-out channels—short, crescentic valleys formed in the face of a slope by waters diverted away from the ice margin for short distances. Types 1 and 2 form aligned sequences, where two or more valleys were connected by continuous channels, and also successive sequences, representing repeated trenching of the same spur.[46]

The terraces and channels are developed along the mountain slopes which lie inside the border of glacial drift shown in Figure 3 and are especially prominent between Big Creek and Stricklin Creek, where at least eight well-defined levels may be identified. On the east side of the valley, channels can be recognized between Emigrant and Six Mile creeks, but associated terraces are largely absent. The channels have been eroded through all the intertributary ridges and irregular spurs lying normal to the ice margin and may be correlated with terraces along the slopes of the larger valleys (Figs. 8 and 9). There is no evidence of glacial deposition or abrasion within the channels. Terraces and channels together form an intricate drainage system developed marginal to the ice as the Yellowstone Glacier slowly melted down and receded up the main valley. It is probable that both lacustrine and slack-water conditions existed within the tributary valleys during various stages of recession.

Along Dry Creek the lowest terrace is 60 feet above the main valley at an elevation of about 5,000 feet, and from this point suc-

[44] P. F. Kendall, "A System of Glacier Lakes in the Cleveland Hills," *Quart. Jour. Geol. Soc.*, Vol. LVIII (1902), pp. 481–87; R. S. Tarr, "Some Phenomena of the Glacier Margin in the Yakutat Bay Region, Alaska," *Zeits. f. Gletscherkunde*, Band III (1908), S. 81–110; John L. Rich, "Marginal Glacial Drainage Features in the Finger Lake Region," *Jour Geol.*, Vol. XVI (1908), pp. 527–48; "Notes on the Physiography and Glacial Geology of the Northern Catskill Mountains," *Amer. Jour. Sci.*, Vol. XXXIX (4th ser., 1915), pp. 137–66; Richard Foster Flint, "The Glacial Geology of Connecticut," *Conn. Geol. and Nat. Hist. Surv., Bull. 47* (1929), pp. 60 and 112–15; "Glacial Features of the Southern Okanogan Region," *Bull. Geol. Soc. Amer.*, Vol. XLVI (1935), pp. 169–94.

[45] *Op. cit.*, pp. 481–83. [46] *Ibid.*, pp. 483–84.

cessive terraces, ranging in height from 40 to 160 feet, are found up to about 6,000 feet. Near the head of the valley the upper limit of early Wisconsin drift is at 6,500 feet. Both the terraces and the channel floors slope to the north, the declivities of the latter being much

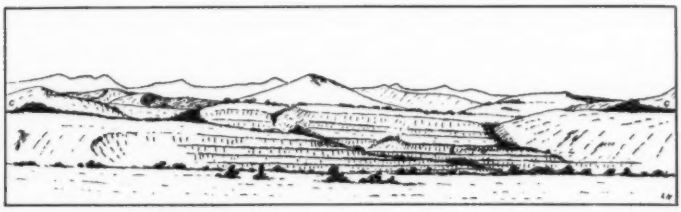

FIG. 8.—Ice-margin terraces along the valley of Dry Creek, Gallatin Range, Montana. The terraces slope gently to the north (*right*) and can be correlated with steep-walled channels (*c*) which cut across adjacent ridges. Flat benches above the terraces represent the broad valley (Terrace No. 2) stage.

FIG. 9.—Ice-margin channels cutting across the ridge south of Stricklin Creek with terrace in the foreground, Gallatin Range, Montana. The view is to the southwest, parallel to the Yellowstone Valley.

the steeper. The trend and depth of the spillways are dependent on the preglacial topography. All the channels of the Gallatin Range have been eroded in coarse, volcanic breccias and have almost vertical walls which range in height from a few feet to over 200 feet (Fig. 9). The mouths of the channels often exhibit parallel ridges of boulders, doubtless formed as bars when the velocity of the water

was checked as it escaped the confines of the narrow, steep channels. One of the most continuous channels in the area extends from the foot of the mountains south of Eight Mile Creek south almost to Stricklin Creek, a distance of over 5 miles. Measurement of terraces along Dry Creek shows that the lower terraces are better developed and are found at shorter intervals than those at higher elevations. This suggests more rapid ablation and fewer halts during the early stages of recession. The pre-eminence of these features along the west side of the valley, rather than the east, is due largely to differences in the underlying bedrock, the volcanic breccias of the Gallatin Range being more readily eroded than the crystalline rocks of the South Snowy block.

After withdrawal of the ice from the valley, the tributary streams resumed their former courses within preglacial valleys in the mountains but probably took new paths across the main valley floor to the Yellowstone. A minor exception to this is noted at the mouth of Stricklin Creek canyon where the preglacial valley was buried by till and terrace materials so that the present narrow gorge has resulted from superposition onto volcanic breccias a short distance north of the old course.

LATE WISCONSIN (PINEDALE) SUBSTAGE

Yellowstone Valley.—During the late Wisconsin substage the Yellowstone Glacier reached a point about 2 miles north of Emigrant. South from that point the drift margin is marked by a well-defined terminal moraine fringed by a narrow outwash apron and numerous outlet channels. West of the river there is no evidence that the ice reached beyond the western edge of the present inner valley. Striae on the basalt near "White Cliffs" indicate that movement was about N. 30° E. at that point. Within the area covered by ground moraine the drift is relatively thin, except where recessional ridges rise above the average level. Constructional forms dominate broad areas, and numerous swamps and small ponds are characteristic. Duck Lake, on the east side of the basalt mesa, is thought to occupy a basin eroded in weak Tertiary "lake beds" and modified by irregular deposition of drift about its border.

As was the case in the earlier invasion, glaciofluvial processes were

active during the recessional stages. This is indicated by the presence of widespread kamelike features, numerous recessional outwash channels, and a well-developed frontal outwash plain and valley train. Recessional channels of unusual size are to be noted east of the basalt mesa where one has cut down through the basalt (Fig. 3) and another heads in the ground moraine west of Six Mile Creek. A third channel, followed by the old wagon road from Emigrant to Emigrant Creek canyon, merges with the terrace along Emigrant Creek near the mouth of the canyon. It is thought that both Emigrant Creek and the abandoned channel carried outwash and fluvial materials during recession of the ice and that the steeper gradient of Emigrant Creek caused it to become the permanent channel of the stream in postglacial time. The thickness and extent of late Wisconsin ice in the southern part of the valley was not determined, because of the uncertainties attending the differentiation of the scattered drift remnants on the mountain slopes. Periglacial phenomena in the form of fossil stone meshes and stripes[47] modify the drift on the basalt plateau and record a continuation of rigorous climatic conditions for some time after withdrawal of the ice from the immediate area.

Adjacent mountains.—The distribution of late Wisconsin moraines, shown in Figure 3, indicates the extent of the larger valley glaciers of late Wisconsin age, and it is probable that detailed studies within the mountainous areas would reveal numerous small moraines and fresh cirques high in the smaller valleys and tributaries. Along the margin of the North Snowy block, the moraines are largely confined between the high lateral moraines of the early Wisconsin glaciers. However, breaching of these older moraines permitted the lobate terminal portions to spread out in front of the older deposits (Fig. 3). Topographically the younger moraines are less conspicuous than those of the preceding substage and are marked by sharp knob-and-basin topography of relatively slight relief. Prominent lateral ridges are absent, and there is a pronounced control exerted by preexisting topography. Terraces at the mouth of Pine Creek show that glaciofluvial activity related to the Pine Creek Glacier continued

[47] Ernst Antevs, *Alpine Zone of Mt. Washington Range* (Auburn, Me.: Merrill & Webber Co., 1932), pp. 53–58.

after completion of the late Wisconsin outwash terrace in the main valley.

In the Gallatin Range only the valleys of Big Creek and Tom Minor Creek appear to have been occupied by late Wisconsin ice, and in the latter the ice was probably tributary to the Yellowstone Glacier as no terminal moraine is evident. The terminal moraine along Big Creek is $\frac{1}{4}$ mile above the Gallatin National Forest entrance and is fronted by a valley train. Located within the inner valley of the stream, these features are 500 feet below the early Wisconsin drift of the Yellowstone Glacier deposited on No. 2 bench.[48] The existence of a temporary lake behind the moraine is evidenced by swampy conditions above the point where it crosses the valley and by a section along the road which shows a peat horizon overlain by varved silts.

In their degree of weathering, dissection, and topographic relations the moraines are similar to the youngest drift found elsewhere in the Rocky Mountains and are correlated with the Pinedale moraines of western Wyoming.

ACKNOWLEDGMENTS.—Acknowledgments are due to Professor R. T. Chamberlin and E. C. H. Lammers of the Yellowstone-Bighorn Research Association for advice and criticism both in the field and in the office; to Richard White and Jack Rinker, Jr., for assistance in the field; and to John Hepburn, Dr. C. E. Marshall, and Vincent Evans, residents of the area, for many kindnesses. The manuscript has profited through criticism by Harold W. Scott and Robert P. Sharp, of the University of Illinois.

[48] Alden, *op. cit.*, p. 52.

CLEAVAGE IN CALCAREOUS SHALES

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ABSTRACT

Microscopic examination of oriented thin sections made from specimens of calcareous shales with well-developed cleavage reveals many thin seams of argillaceous material parallel to the direction of cleavage. Evidence is advanced to prove that these clay seams are insoluble residues formed by solution under pressure along pre-existing planes of microscopic shearing.

INTRODUCTION

The shales in the central section of the Valley of Virginia which have the most perfect cleavage are those containing about 50 per cent calcium carbonate. These shales belong to the thick Athens and Martinsburg formations of Ordovician age. The cleavage, which the writer believes to be a variety of fracture cleavage, is so perfect and the planes are so closely spaced that the structure has been mistakenly described as slaty cleavage.[1] In an effort to explain the relationship between cleavage and composition, a field and laboratory study was made of the structure in 1937 and 1938. The purpose of this paper is to present for criticism the conclusions resulting from these studies.

FIELD OBSERVATIONS

Wherever the cleavage was observed the shales are folded into small open folds which are slightly overturned to the northwest. The planes of parting, which divide the rock into sheets of paper thinness, are almost parallel to the axial planes of the folds. As a result the structure is easily confused with slaty or flow cleavage. In several places, however, close examination shows that in passing from one bed to another the cleavage planes change as much as 5° in dip. In one locality, 9 miles west of Lexington, the surfaces of parting can be seen to curve around the edges of small nodular

[1] C. Butts and J. K. Roberts, "Charlottesville to West Virginia by Way of Waynesboro, Staunton, and Monterey," *XVI Internat. Geol. Cong. Guidebook 11* (1933), Pl. III.

bryozoans. Near Fincastle, Virginia, where the Athens formation locally contains pebbles of Cambrian quartzite,[2] the cleavage surfaces curve around the pebbles. These observations indicate that the cleavage is not the result of rock flowage but rather that of shearing. Furthermore, if the cleavage were true slaty cleavage, one would expect the structure to be as well developed, if not better developed, in shales containing no calcium carbonate. Such is not the case.

RELATIONSHIP BETWEEN CLEAVAGE AND COMPOSITION

In order to check the field observation that the cleavage is definitely related to the amount of calcium carbonate in the shale, a suite of specimens was collected between North Mountain, which bounds the Valley on the northwest, and the Blue Ridge Range, which lies to the southeast. Hand specimens of every type of shale and limestone outcropping in the Valley were collected regardless of whether the rock had cleavage or not. Care was taken to obtain specimens which had not been weathered.

Each of the specimens was treated with hydrochloric acid to determine the percentage of carbonates. It was learned that all those specimens which exhibited well-developed cleavage contained between 40 and 55 per cent calcium carbonate. Those specimens which had poor cleavage or no cleavage at all contained either a greater or a lesser amount of soluble material.

PETROGRAPHY

Microscopic examination of oriented thin sections made from specimens with good cleavage reveals the fact that the so-called calcareous shales are in reality impure limestones containing many thin seams of argillaceous material. These microscopic bands of clay cut across the bedding planes of the limestone and are parallel to the direction of cleavage. In some thin sections there are as many as 240 clay bands to the inch. Figure 1 is a photomicrograph of such a section.

Since the cleavage in the rock is so obviously related to the dis-

[2] M. H. Stow and J. C. Bierer, "The Significance of an Athens Conglomerate near Fincastle, Virginia," *Proc. Va. Acad. Sci., 1937*, p. 71.

tribution of materials, a careful search was made for evidence of rock flowage. None was found. The elongated grains in the impure limestone are oriented at random. Tiny fossils in the limestone have not been rotated to positions approaching parallelism with the clay bands; nor have these fossils been granulated.

FIG. 1.—Photomicrograph of thin section of calcareous shale showing clay seams which are parallel to the direction of cleavage. (Uncrossed nicols; ×40.)

The similarity between the particles in the clay seams and the impurities in the limestone suggested the possibility that the seams might be insoluble residues resulting from solution along fractures formed by shearing. There are several types of evidence which confirm this hypothesis. Fossils found in the thicker bands of impure limestone terminate abruptly at the clay seams bounding the limestone bands (Fig. 2). In many instances it is apparent that the ends of the fossils are missing (Fig. 3). These microscopic characteristics are similar to those macroscopic ones interpreted as resulting from

solution in the formation of stylolites.[3] Where a clay band cuts across two beds of limestone of differing purity, the clay band is thinner where it crosses the purer limestone layer than in the less pure layer. In those thin sections where the cleavage meets the bedding at an acute angle, it has been noted that the bedding planes

FIG. 2.—Photomicrograph of thin section of calcareous shale. Note that fossils do not cross the thick clay seam. (Uncrossed nicols; ×40.)

have been slightly offset by the clay seams. The amount of offset is not uniform or haphazard but bears a definite relation to the thickness of the clay seam. Large offsets occur at thick clay seams, small offsets being associated with thin ones. In every case the direction of offset is such as can be explained by the removal of material by solution under pressure.

[3] W. H. Twenhofel, *Treatise on Sedimentation* (Baltimore: Williams & Wilkins Co., 1932), p. 738.

EVIDENCE AS TO THE TIME OF SOLUTION AND THE NATURE OF THE SOLVENT

Since the shales with well-developed cleavage are very compact today and since no open fractures were observed in any of the thin sections, it is believed that the solution which produced the clay

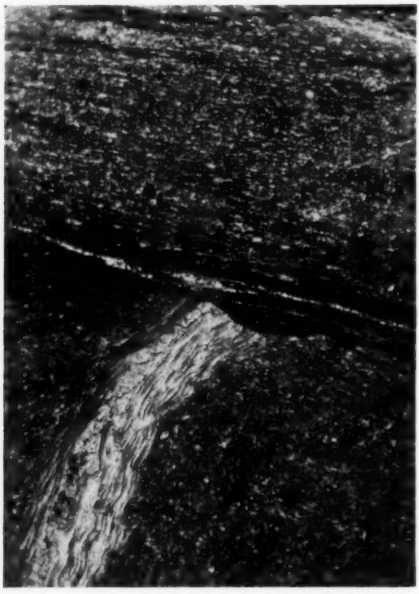

FIG. 3.—Photomicrograph of thin section of calcareous shale. Note that the end of the fossil is cut off where the fossil meets the clay seams. (Uncrossed nicols; ×40.)

seams must have taken place shortly after the original fractures had been formed, while the rocks were still under considerable pressure. Although the solution may have been caused by either ascending or descending ground water, stratigraphic evidence favors the latter. The calcareous shales under discussion lie at the base of the Martinsburg formation and at the base of the Athens formation. The upper portions of both of these formations are composed of noncalcareous shales. Therefore, descending ground water would not be likely to

contain very much calcium carbonate in solution when it first reached the calcareous shales. On the other hand, since both formations overlie comparatively thick limestones, ascending ground water would undoubtedly be saturated with calcium carbonate before coming in contact with the shales.

CONCLUSION

Among the adjustments which take place when sedimentary rocks are folded at depth is microscopic shearing. The fractures produced by such shearing are seldom preserved, since they are readily healed under prolonged confining stresses. If, however, as in the case of the calcareous shales described, ground water should remove certain soluble minerals along these minute shear planes before they had completely healed, a microscopically banded rock would result, in which the alternating bands of different composition would parallel the original shear structure. A similar structure could be produced in pure limestones if ground water replaced the calcite grains bordering the microscopic shear planes by some other mineral such as chert. In the case of those rocks which are predominantly clastic, a microscopically banded rock could be formed by the deposition of some foreign material along the shear planes. In all these instances the observed cleavage would be the direct result of an orderly distribution of the materials composing the rocks rather than the immediate result of the original fractures developed when these rocks were first deformed.

ACKNOWLEDGMENTS.—The writer is greatly indebted to Dr. M. H. Stow, who not only took the photomicrographs but also read and criticized the manuscript. Several valuable suggestions were made by Dr. R. T. Chamberlin during the course of the field and laboratory work.

SUMMER FIELD COURSES IN GEOLOGY

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ABSTRACT

Seventy-four organized summer field courses in geology are offered by universities and colleges in the United States. Forty-eight of these are open to properly qualified students from outside institutions, and admission to some of the others may be obtained by special arrangement. A digest and summary of information concerning these courses is presented.

INTRODUCTION

A consideration of the problems of field work for University of Illinois students prompted a survey of summer courses in field geology. The information obtained appears to be of such general interest that it is made available to everyone. Evaluation of the various courses is left to the individual, and no attempt is made to discuss the philosophical aspects of the subject, for that has already been done in an excellent manner by Patton.[1] Questionnaires were sent to 210 institutions, and 177 replies were received, many of which were accompanied by lengthy voluntary letters, circulars, or various other types of additional information. The wholehearted co-operation of the many institutions and individuals approached is gratefully acknowledged. This survey was sponsored and supported by the Department of Geology and Geography of the University of Illinois. In several instances information is kept confidential on request.

DIGEST OF FIELD COURSES

A total of 74 organized summer field courses in geology has been reported. This includes courses based at permanent camps, in temporary quarters, or on tour. The geographic distribution of field courses by states, not including tours, is as follows: Colorado, 7; Wyoming, 7; California, 5; South Dakota, 5; Virginia, 4; Montana, 3; Pennsylvania, 3; Texas, 3; Arizona, 2; Michigan, 2; Minnesota, 2; Missouri, 2; Nevada, 2; Washington, 2; Wisconsin, 2; New

[1] Leroy T. Patton, "Geological Field-Courses in American Colleges," *Pan-Amer. Geol.*, Vol. LX (1933), pp. 25–33.

Mexico, 1; New York, 1; North Carolina, 1; Oklahoma, 1; Oregon, 1; Tennessee, 1; Utah, 1; West Virginia, 1; and Canada, 2. This distribution is about as would be expected, with the Rocky Mountains leading all other areas by a large margin and followed by the Appalachians, the Black Hills, the California Coast Ranges, and the Lake Superior region in that order. Touring trips run to various parts of the United States, Canada, and Mexico, but the western states are most favored.

Nearly every conceivable phase of geology is covered, and various types of field mapping, from broad reconnaissance to intensely detailed work with plane table and alidade, are offered. Many camps give a combination of several types of field study including instruction in surveying and underground mapping, and in some cases the courses in geology are given in conjunction with allied sciences, such as biology, botany, surveying, engineering, and mining. Some of the touring trips include mapping in chosen areas, and some of the courses based on areas around more or less permanent camps include a tour to or from the field area or short excursions into neighboring regions. Final reports are a usual but not universal requirement. Most courses require previous training of at least a semester or year of elementary physical geology, and many have prerequisites which include historical geology, mineralogy, petrology, structural geology, surveying, and allied courses. A few are designed for students without any previous geological instruction.

A moderate number of institutions have camps equipped with permanent buildings, while others rely on local accommodations or camping equipment and may change locale from year to year. Most courses start in early summer and last 3–10 weeks with an average of 5–6 weeks; a few are given twice during the summer. Many are limited solely to men and a few entirely to women; however, a large number admit both men and women, and there is abundant opportunity for women to take summer field work. The number of students ranges from 5 or 6 to 50 or 60, and the average ratio of students to instructors is about 9.5 to 1. This ratio and its significance have been discussed by Patton.[2]

The average cost for a 5–6 weeks' course is $100–$125. This does

[2] *Ibid.*, pp. 27–28.

not include transportation to and from the camp or extraneous personal expenditures, but it does include tuition, fees, and all expenses associated with the camp including the transportation involved in field work. Usually, tours covering a corresponding period are somewhat more expensive, but, of course, this cost includes all transportation from start to finish.

For courses in which a final report is required, the average credit given is about 1 semester hour for each week in the field. For courses without a final report it is about 1 hour for each 2 weeks in the field. The credit offered is seldom higher than this, and not infrequently it is lower.

Many institutions and organizations offer considerable opportunity for advanced work in connection with their program of field instruction, either in organized courses or as supervised individual work which may be suitable for an advanced degree. Notable along this line is the Yellowstone-Bighorn Association which is engaged almost wholly in research work of an advanced nature.

EXPLANATION OF TABLES

The courses listed in the following tables have been divided into two groups. Group A (Table 1) includes all courses in which properly qualified students from outside institutions are encouraged to enrol or are admitted if room is available. Group B (Table 2) includes those courses in which outside students are not accepted or accepted only under special conditions. Group B contains many excellent field courses, and students may be able to gain admission to them by making special arrangements with the institutions concerned. The tables give the cost to the student after reaching camp. This does not include traveling expenses to or from camp, except in the case of tours in which cost of all transportation is included. Credits are expressed in semester hours.

The reader should realize that field programs are in a constant state of change; hence, at least some of the material included herein will be out of date within a short time. Students and their advisers will find that circulars and catalogues published by various institutions give much additional information. Inquiries should be directed to the institution concerned.

TABLE 1

GROUP A. COURSES FOR WHICH PROPERLY QUALIFIED STUDENTS ARE SOLICITED, ENCOURAGED TO ATTEND, OR ACCEPTED IF ROOM IS AVAILABLE

Institution	Locale	Time	Personnel	Cost	Prerequisites	Subjects Stressed	Nature of Work and Credit
Arizona, Museum of Northern, and Arizona State Teachers College, Flagstaff, Ariz.	San Francisco Mountains, Grand Canyon, and Painted Desert, Arizona; permanent buildings	First time in 1940; 6 weeks, late June to early August	Men; 3–4 instructors	$180	Elementary course in geology; preference to graduate students	Vulcanology, geology of pre-Cambrian, Paleozoic, and Mesozoic rocks	Probably field mapping, short trips to neighboring areas, final report; credit not yet determined; opportunity for advanced work
Baylor University, Waco, Tex.	Appalachian highlands, Piedmont, Atlantic coastal plain; temporary quarters	Annually; first time in 1940; 4½ weeks, mid-June to mid-July	Men and women; 1 instructor	$140	Elementary knowledge of theory and practice of electrical and magnetic methods of geophysical prospecting	Field methods and interpretation of geophysical surveying and study of associated geological features	Geophysical surveying, final report; 5 hours credit; opportunity for advanced work
California, Univerity of, at Los Angeles, Los Angeles, Calif.	Southern California; temporary camps	First offered in 1941; 6 weeks, June 10–July 22	Men, 25–30; 2 instructors	$100	Surveying, mineralogy, petrology, physical and historical geology, field methods; upper division standing	Tertiary stratigraphy and structure	Field mapping, optional plane table work, final report; 4 semester units credit
Chicago, University of, Chicago, Ill.	Course 208. Devils Lake, Baraboo, Wis.; permanent building	Annually; 1 month, mid-August to mid-September	Men and women, 12; 1 instructor	$100	1 year of college geology	Pre-Cambrian rocks, early Paleozoics, glaciation, geomorphology	Field mapping, final report for majors; limited opportunity for advanced work
	Course 209. Ste Genevieve County, Mo.; permanent buildings	Annually; 1 month, mid-June to mid-July	Men, rarely women; 9–18; 1 instructor	$100	1 year of college geology	Paleozoic stratigraphy and structural geology	Field mapping, side trips; 4 hours credit without final report, 6 hours credit with report; opportunity for advanced work
Colorado College, Colorado Springs, Colo.	Pikes Peak region, Colorado; college buildings	Annually; 6 weeks, mid-June to late July	Men and women, 8–10; 1 instructor	$100	Physical and historical geology, structure, mineralogy, petrology	General geology, structure, geological and topographic surveying	Field mapping, plane table work; 2 hours credit, more on arrangement; short trips, opportunity for advanced work
Colorado School of Mines, Golden, Colo.	Pueblo and Empire, Colo.; permanent buildings	Annually; 6 weeks, early June to mid-July	Men, 50–60; 3–5 instructors	$91	Historical geology, structure, mineralogy, petrology, surveying	Structure, engineering geology, oil and ore deposits, sedimentary, metamorphic, and igneous rocks	Field mapping, underground work, plane table and transit surveying, final reports; opportunity for advanced work

TABLE 1—*Continued*

Institution	Locale	Time	Personnel	Cost	Prerequisites	Subjects Stressed	Nature of Work and Credit
Colorado, University of, Boulder, Colo.	Geology 115. Front Range of Colorado Rockies; permanent buildings	Twice annually; 5 weeks, June 20–July 25, July 25–August 28	Men and women, 35–40; 3 instructors	$125	1 year of geological work	Pre-Cambrian rocks, Paleozoic, Mesozoic, and Tertiary stratigraphy and structure, geomorphology, glaciation	Field mapping, short trips, final report; 5 hours credit; provision for advanced work
	Geology 120. Northern Colorado Front Range; permanent buildings and temporary camps	On demand, almost annually; 6 weeks, early June to mid-July	Men, 6–10; 1–2 instructors	$125	Advanced knowledge of general, structural, and economic geology, and field methods	Paleozoic and Mesozoic stratigraphy and structure, Tertiary and pre-Cambrian igneous rocks and metamorphism	Field mapping, short trips, plane table work, final report; professional training; 8 hours credit
Columbia University, New York, N.Y.	See University of Wyoming and Group B						
Cornell College, Mount Vernon, Iowa, and Knox College, Galesburg, Ill.	Wind River Range, Wyo.; permanent buildings	Annually; 4 weeks, August 1–29	Men and women; 2 instructors	$100	General geology for advanced work; no previous geology required for beginning course	Paleozoic and Mesozoic stratigraphy and structure, glaciation	Field mapping, plane table work, trip to Yellowstone and Grand Tetons, final report; 6 hours credit; opportunity for advanced work
Cornell University, Ithaca, N.Y.	Central Pennsylvania; permanent buildings	Annually; 6 weeks, mid-June to end of July	Men, 10–12; 1 instructor	$150	Graduate students and upper class majors	Folded Paleozoics of Appalachians	Field mapping, elective plane table work; 6 hours credit; opportunity for advanced work
George Washington University, Washington, D.C.	Virginia, West Virginia, and Maryland	Biennially; 9 weeks, mid-June to end of August	Men and women, 60; 1 instructor	.....	University entrance requirements	Pre-Cambrian, Paleozoic, and Cenozoic stratigraphy and structure	Collections and notebook, 6 hours credit; opportunity for advanced work
Hunter College of New York, New York, N.Y.	New York State	Annually; 12 days, mid-June to end of July	Women, 16–18; 2 instructors	$80	Dynamic, physical, and historical geology	Pre-Cambrian rocks, Paleozoic stratigraphy, geomorphology, glaciation	Tour, final report; 3 hours credit
Iowa, University of, Iowa City, Iowa	Black Hills, S.D.; permanent buildings	Annually; 4 weeks, mid-June to early July	Men and rarely women, 15–18; 2 instructors	$86	1 year general physical and historical geology	Paleozoic, Mesozoic, and Cenozoic stratigraphy and structure, igneous geology, geomorphology	Field mapping, final report; 6 hours credit; some opportunity for advanced work following course
	Deadwood-Lead, S.D.; permanent buildings	Annually; 3½ weeks, mid-July to early August	Men, 12; 1 instructor	$75	1 year of general physical and historical geology and preliminary field course	Pre-Cambrian stratigraphy, structure, metamorphism, igneous geology, ore deposits	Field mapping, final report; 5 hours credit; opportunity for advanced work

TABLE 1—*Continued*

Institution	Locale	Time	Personnel	Cost	Prerequisites	Subjects Stressed	Nature of Work and Credit
Kansas, University of, Lawrence, Kan.	Geology 159. Garden Park near Canyon City, Colo.; permanent buildings	Annually; 5 weeks, mid-June to late July	Men, 15; 1–2 instructors	$147.50 (less $40 for residents of Kansas)	1 year of geology	Paleozoic and Mesozoic stratigraphy and structure	Field mapping, short trips, plane table work, final report; 5 hours credit; opportunity for advanced work
	Geology 359. Western states	Annually; 5 weeks, August 1–September 5	Men and women, 10–15; 1 instructor	$180 (nonresidents add $30, and new students add $20)	Completion of undergraduate major in geology and one 5-hour field course	Regional stratigraphy and correlation, invertebrate paleontology, structure, mineralogy, petrology, economic geology, geomorphology	Tour, final report; 5 hours credit; opportunity for advanced work in addition to course
Kentucky, University of, Lexington, Ky.	New England, northern Appalachians, or western states, different each year	Annually; 3 weeks, June 1–21	Men, 10–15; 2 instructors	$60	2 years of geology	Wide range of geological features	Tour, examination; 2 hours credit
Knox College, Galesburg, Ill.	See Cornell College, Iowa						
Michigan College of Mining and Technology, Houghton, Mich.	Course Y-160. Northern Wisconsin and Michigan; temporary quarters	Annually; 3 weeks, mid-July to early August	Men and women, 20; 1–2 instructors	$80–$100	General geology, mineralogy, petrology	Cambrian and early Paleozoic structure and stratigraphy, economic geology, Tertiary structure and mineralization, glaciation	Field mapping, trips, notebook; 3 hours credit; opportunity for advanced work
	Course Y-161. Lake Superior region; temporary quarters	Annually, if demanded; 2 weeks, from mid-August or 1st of September	Men and women, 5–10; 1 instructor	$60–$75	Preceding course, Y-160	Pre-Cambrian stratigraphy and structure, economic geology, Tertiary structure and mineralization	Field mapping, final report; 2 hours credit; advanced work possible
Michigan State College, East Lansing, Mich.	Near Marquette, Mich.; temporary quarters	Annually; 15–20 days, September 1–20	Men, 12; 1 instructor	$27.50	General geology, mineralogy, petrology, structure, mapping or surveying	Pre-Cambrian geology, metamorphism, economic geology	Field mapping, some plane table work, final report, 3 term-hour credits; advanced work possible
Michigan, University of, Ann Arbor, Mich.	Jackson Hole, Gros Ventre, and Teton Mountains, Hoback and Snake River valleys, Wyoming; permanent buildings	Annually; 8 weeks, June 20 to mid-August	Men and women, 22; 3 instructors	$150 (includes transportation from Ann Arbor to camp)	Introductory geology courses, better than a C average	Stratigraphy, structure, physiography, and igneous rocks	Field mapping, tour from Ann Arbor to camp, plane table work, reports; 8 hours credit; provision for advanced work

TABLE 1—*Continued*

Institution	Locale	Time	Personnel	Cost	Prerequisites	Subjects Stressed	Nature of Work and Credit
Minnesota, University of, Minneapolis, Minn.	Course 855*m*. Iron Ranges in Northeastern Minnesota; temporary quarters	Annually; 2 weeks, July 15–30	Men, 35–40; 2 instructors	$65	General geology, mineralogy, and rock study	Geology of pre-Cambrian rocks	Field mapping, final report; 3 hours credit, advanced work possible
	Course 1505*m*. Black Hills, S.D.; temporary camps	Annually; 4 weeks, September	Men, 10–15; 1 instructor	$100	General geology, structure and ore deposits	Paleozoic and Tertiary structure and stratigraphy	Field mapping, plane table work, final report; 6 hours credit; advanced work possible
Mississippi State College, State College, Miss.	Western states, Canada, Alaska, and Mexico	Annually; 60 days, June 10 to early August	Men and women, 18; 1–2 instructors	$175–$200	No prerequisites for the general course	General geology and geography	Tour, final report; 6 hours credit; opportunity for advanced work
Missouri, University of, Columbia, Mo.	Wind River Range, Wyo.; permanent buildings	Annually; 7 weeks, mid-June to August 1	Men and women, 35–40; 4 instructors	$98	10 hours of geology for course 105, 18 hours for course 136, undergraduate major and field experience for graduate work	Pre-Cambrian to late Tertiary stratigraphy, structure, paleontology, physiography, economic geology, glaciation	Field mapping, plane table work, final report, side trips; 7–8 hours credit; provision for advanced work
North Carolina, University of, Chapel Hill, N.C.	Blacksburg, Va., and Spruce Pines, N.C.; temporary quarters	Annually; 6 weeks, early June to mid-July	Usually men, 10–12; 1–2 instructors	$125	General geology, mineralogy, lithology, structure, and field geology	Paleozoic stratigraphy, pre-Cambrian rocks, metamorphism, economic geology	Field mapping, final report, plane table work; 10 quarter-hours (6⅔[?] semester-hours) credit; opportunity for advanced work
Northwestern University, Evanston, Ill.	Lake Superior region; temporary camps	Biennially; 4 weeks, given in 1940; August 10–September 10	Men, 15–20; 2 instructors	$110–$115 (from Evanston, Ill., and return)	1 year of college geology, preference given to students with more training	Pre-Cambrian rocks, geology of Iron Ranges, field methods	Field mapping, final report, some plane table work, tour of Iron Ranges; 6 hours credit
Oberlin College, Oberlin, Ohio	Highland County, Va.; temporary camp	Annually, on demand; 7 weeks, June 15–August 1	Men and women, 6; 1–2 instructors	$130	8 hours of beginning geology, more advanced courses desirable	Paleozoic stratigraphy and paleontology, physiography, igneous rocks, surveying	Field mapping, plane table work, final report; 8 hours credit; some opportunity for advanced work
Ohio State University, Columbus, Ohio	Near Dayton, Tenn.; temporary quarters	Annually; 5 weeks, June 15–July 20	Men, 10; 1 instructor	$100 (from Columbus and return, and $40 for out-of-state men)	At least 1 year of work in geology, Junior rank, permission of instructor	Paleozoic stratigraphy, geomorphology	Field mapping, plane table work, final report; 8 quarter-hours (5⅓[?] semester hours) credit; opportunity for advanced work
Oregon State College, Corvallis, Ore.	Cascade Range and other Oregon localities; temporary camps	Annually; 6 weeks, June 10–July 20	Men, 10; 1 instructor	$50	At least 1 full-year course in geology, more desirable	Structural, stratigraphic, and igneous geology	Field mapping, plane table work, side trips, final report; 10 credits (6⅔[?] hours); opportunity for advanced work

TABLE 1—*Continued*

Institution	Locale	Time	Personnel	Cost	Prerequisites	Subjects Stressed	Nature of Work and Credit
Pennsylvania State College, State College, Pa.	Geology 72. Near State College, Pa.; permanent buildings	Annually; 8 weeks, June 10–August 3	Men and women, 20; 2 instructors	$108–$123 (including cost of tour)	Physical and historical geology, surveying desirable	Pre-Cambrian, Paleozoic, and Mesozoic geology, economic geology	Field mapping, plane table work, tour of eastern United States, final report; 8 hours credit; some advanced work; also short 3-hour course for petroleum engineers (Geology 70)
Princeton University, Summer School of Geology and Natural Resources, Princeton, N.J.	General trip: Princeton to Far West, end at Red Lodge, Mont. Oil trip: Red Lodge to New Jersey	Annually; 5–6 weeks starting at close of college; oil trip on occasions	Men, 15; 2 instructors and local guides and instructors	$200–$265	Introductory geology for general trip; general geology and structure for oil trip	General trip touches all phases of geology; oil trip concentrates on petroleum geology, drilling methods, and related subjects	General course is tour with final examination; 3 hours credit. Oil trip has some detailed mapping, and areas of active exploration and development are visited
Puget Sound, College of, Tacoma, Wash.	Olympic Peninsula, Rainier Park, Wash.; temporary camps	Occasionally; 4–5 weeks, July to August	Men, 5–10; 1 instructor	.....	8 hours of general and historical geology	Metamorphic rocks, Tertiary structure and stratigraphy, volcanics, geomorphology, glaciation	Field mapping, final report; 4–5 hours credit
Smith College, Northampton, Mass.	Black Hills, Bear Lodge, Big Horn Mountains, Wyo. and S.D.; temporary quarters	Almost annually; 6 weeks, June 25–August 5	Women, 10–12; 2 instructors, chaperon	$250	Elementary geology	Pre-Cambrian rocks, Paleozoic, Mesozoic, and Tertiary stratigraphy and structure, geomorphology	Usually field mapping; 6 hours credit with examination; 8 hours credit with report; opportunity for advanced work
Southern California, University of, Los Angeles, Calif.	Ventura Basin, Southern Calif.; temporary camps	Occasionally; 6 weeks, mid-June to August; not offered in 1940	Men and women, 6; 1 instructor	$125	Mineralogy, petrology, structure, invertebrate paleontology	Tertiary structure and stratigraphy, field methods	Field mapping, some plane table work, final report; 4–6 hours credit; opportunity for advanced work
Stanford University, Palo Alto, Calif.	Southern California Coast Ranges and/or Great Basin; temporary camps	Annually; 10 weeks, June 20–September 1	Men, 20–30; 1 instructor for every 6 students	$210 (less reund)	Elementary and historical geology, mineralogy, petrology, surveying	Paleozoic, Mesozoic, and Tertiary stratigraphy and structure, igneous rocks, geomorphology	Field mapping, plane table work, final report; 15 quarter units (about 10 semester-hours) credit; opportunity for advanced work
Texas, Agriculture and Mechanical College of, College Station, Tex.	Wind River Range, Wyo., or other areas; temporary camps	Annually; 6 weeks, July 15–September 1	Men, 15; 2 instructors	$125	General geology mineralogy; approval of head of department	Early Paleozoic stratigraphy and structure, geomorphology	Field mapping, plane table work, final report; 7 hours credit; opportunity for advanced work

TABLE 1—*Continued*

Institution	Locale	Time	Personnel	Cost	Prerequisites	Subjects Stressed	Nature of Work and Credit
Texas Technological College, Lubbock, Tex.	Colorado or New Mexico; temporary camps	Twice annually; 6 weeks, early June to mid-July, mid-July to late August	Men, 12; 1 instructor	$75	1 year of general geology, usually 12–18 hours	Many phases of geology, particularly sedimentary rocks, stratigraphy, and structure	Field mapping, plane table work, final report; 6 hours credit; opportunity for advanced work
Texas, University of, Austin, Tex.	Even years in Central Mineral district of Texas; odd years in Austin region; permanent buildings	Twice annually; 6 weeks, early June to mid-July, mid-July to late August	Men, 30; 3–4 instructors, 1–2 assistants	$80	General geology, mineralogy, paleontology, plane surveying, drawing	Paleozoic stratigraphy and structure on even years; Mesozoic stratigraphy and structure on odd years	Field mapping, plane table work, final report, short tours; 6 hours credit; opportunity for advanced work
Utah, University of, Salt Lake City, Utah	Wasatch Mountains, Wasatch Plateau, Uinta Mountains; temporary quarters	Annually; 6 weeks, mid-August to late September	Men and women, 8–10; 1 instructor	$90	Physical, historical, and structural geology, petrology	Pre-Cambrian to Tertiary structure and stratigraphy	Field mapping, may be some plane table work, final report; about 5½ hours credit
Vassar College, Poughkeepsie, N.Y.	See University of Wyoming						
Virginia Polytechnic Institute, Blacksburg, Va.	Central Virginia near Blacksburg College buildings	Annually; 3–6 weeks, early June to July	.....	.....	Fundamental courses in geology, graduates preferred	Appalachian structure and stratigraphy, igneous and metamorphic geology, mining geology	Field methods, some plane table work, short trips and sometimes tour
Washington State College, Pullman, Wash.	Pacific Northwest, usually Washington; temporary camps	Annually; 4–8 weeks, starting in mid-June	Men, rarely women, 8–10; 2 instructors	$50–$125	1 year college geology, 3 years preferred; admission by arrangement	Paleozoic, Mesozoic, Tertiary structure and stratigraphy, geomorphology, petrology, metamorphism; varies with region	Field mapping usual, some plane table work, final report for advanced students; 4 hours credit for 4 weeks, more at same ratio; graduate work stressed
Wellesley College, Wellesley, Mass.	Glacier National Park, Mont.; temporary quarters	Annually; 3 weeks, late July to early August	Women, 7; 1 instructor	$175	1 year course in physical and historical geology	Pre-Cambrian stratigraphy and structure, geomorphology, glaciation	Field mapping, final report, pack trip; 3 hours credit
West Virginia University, Morgantown, W.Va.	Pendleton County, W.Va.; temporary quarters	Annually; 6 weeks, June 10–June 15	Men and women, 6; 1 instructor	$90	Physical, historical, and structural geology	Appalachian structure and stratigraphy, geomorphology	Field mapping, plane table work, final report; 6 hours credit

TABLE 1—*Continued*

Institution	Locale	Time	Personnel	Cost	Prerequisites	Subjects Stressed	Nature of Work and Credit
Wheaton College, Wheaton, Ill.	Black Hills, S.D.; permanent buildings	Annually; 4 weeks, July 20–August 20	Men and women, 15; 2 instructors	$75	Sufficient preparation to carry on work desired	Tertiary structure and stratigraphy, glaciation	Some field mapping, plane table work, usually final report; 2–5 hours credit; several courses offered, opportunity for advanced work, some extension trips
Wyoming, University of, Laramie, Wyo. (co-operative with Columbia and Vassar)	Medicine Bow Mountains and adjacent parts of Wyoming; permanent buildings and temporary camps	Annually; 5 weeks, late mid-June to late July	Men and women, 40–50; 5 instructors	$133.50	For elementary course need only college standing; for advanced course need Junior standing and 2 years' work in geology	Pre-Cambrian, Paleozoic, Mesozoic, and Tertiary structure and stratigraphy, field methods, geomorphology, igneous geology, economic geology	Field mapping, plane table work, 2,000 miles covered on trips; 6 hours credit; opportunity for advanced work with Wyoming State Survey
Yellowstone-Bighorn Research Association, W. T. Thom, secretary, Princeton University	Region adjacent to Yellowstone Park and Bighorn Basin; headquarters at leased camp near Red Lodge, Mont.	Annually; usually 2 months, July and August	Chiefly men, normally 15 faculty, 12 graduate students 25 undergraduates, and 6–8 preparatory students	Small, depends upon work	Arranged individually	All phases of geology	Field mapping, plane table work, report optional; credit to be arranged, none given by the Association; opportunity for all varieties of advanced work

TABLE 2

GROUP B. COURSES FOR WHICH OUTSIDE STUDENTS ARE ACCEPTED ONLY UNDER SPECIAL CONDITIONS OR NOT AT ALL

Institution	Locale	Time	Personnel	Cost	Prerequisites	Subjects Stressed	Nature of Work and Credit
Alfred University, Alfred, N.Y.	Western New York, Allegany County; temporary quarters	Annually on demand; 17 days, early to late June	.....	$34 (not including board and room)	.....	Stratigraphy, geomorphology, glaciation, Devonian paleontology	Field studies and short trips
Arizona, University of, Tucson, Ariz.	Arizona, probably southern part; temporary camps	Not offered at present, possibly by 1941; 4–8 weeks	Men, 12; 2 instructors	$85 for 4 weeks, $130 for 8 weeks	Physical and historical geology, mineralogy, petrology, surveying	Paleozoic and Mesozoic stratigraphy and structure, igneous intrusions, volcanics, physiography, surveying, economic geology	Field mapping, plane table work, final report; 3 hours credit for 4 weeks, 6 hours for 8 weeks
Barnard College, New York, N.Y.	New York, Pennsylvania, New Jersey; temporary quarters	Occasionally; 3 weeks immediately after academic year	Women, 8; 1 instructor	.....	1 year of general geology	Paleozoic stratigraphy, geomorphology, structural and economic features	Field mapping, final report; 3 hours credit
California Institution of Technology, Pasadena, Calif.	Even years in California Coast Ranges, odd years in Great Basin; temporary camps	Annually; 4½–5 weeks, second week of June to mid-July	Men, 20–30; 1 instructor	$75	General and historical geology, structure, mineralogy, 2 terms field geology, plane table surveying	Coast Range Tertiary structure, stratigraphy, and geomorphology; Great Basin, Pre-Cambrian, Paleozoic, Mesozoic, and Tertiary structure and stratigraphy, geomorphology, igneous geology	Field mapping, plane table work, final report; 4 hours credit. Outside students must be admitted to the Institute to enrol; occasionally tour
California, University of, Berkeley, Calif.	Central California Coast Ranges; temporary camps	Annually; 6 weeks, May 15–July 1	Men, 22; 2 instructors	$125	General geology, petrology, field geology	General stratigraphy and structure of California Coast Range Tertiary	Field mapping, some plane table work, final report; 4 hours credit; opportunity for advanced work
Columbia University, New York, N.Y.	Course 278. Ontario, Canada; temporary quarters	Annually; 2–6 weeks, May 25–July 1	Men and women, 10; 1 instructor	$50–$100	Graduate students with field experience in geological mapping	Pre-Cambrian and Paleozoic structure, stratigraphy, and metamorphism	Field mapping, plane table work, final report optional; credit 1 hour per 2 weeks, 1 hour per 1 week with report; opportunity for advanced work
Denver, University of, Denver, Colo.	Denver Mountain Parks quadrangle, Colo.; temporary quarters	Usually annually; 4–5 weeks, June 10–July 10	Men and women, 6; 1–2 instructors	$25	Senior geology students and graduate students working for M.S. or Ph.D. degree	Pre-Cambrian rocks, Paleozoic and Mesozoic stratigraphy and petrology, geomorphology, glaciation, Tertiary intrusives and volcanics	Field mapping, some plane table work, final report; all work of advanced nature on Denver Mountain Parks quadrangle project of University of Denver; 3½ hours credit

TABLE 2—*Continued*

Institution	Locale	Time	Personnel	Cost	Prerequisites	Subjects Stressed	Nature of Work and Credit
Drury College, Springfield, Mo.	Graydon Springs, Polk County, Mo.; permanent buildings	Occasionally; 1 week, early June	Men, 6; 1 instructor	Outside students not accepted	Introductory physical and historical geology	Ordovician, Mississippian, and Pennsylvanian stratigraphy	Field mapping; no credit
Emory and Henry College, Emory, Va.	Southern Appalachian highlands; temporary quarters	Occasionally; 3 weeks	Men and women, 15; 1 instructor	.....	General geology	General geology and geography	Field mapping, final report; 3½ hours credit
Fresno State College, Fresno, Calif.	Southwestern United States or Pacific Northwest	Occasionally; 6 weeks, June 15–August 1	Men, 10; 1 instructor	.....	General geology, mineralogy, physiography	Physiography, mineralogy, Cenozoic and Mesozoic stratigraphy, volcanism, economic geology	Field mapping, final report; 6 hours credit; course varies, tour with local intensive work
Hawaii, University of, Honolulu, Hawaii	Co-operative agreement with Hawaiian Volcano Research Association and the National Park Service whereby qualified persons may use laboratory facilities for geological research at Kilauea						
Louisiana State University, Baton Rouge, La.	Near Colorado Springs, Colo.; permanent buildings	Annually; 9 weeks, June 1 to early August	Men, 50–55; 3–4 instructors	$100	Chiefly seniors, rather advanced training including petrology, structure, etc.	Stratigraphy and structure of rocks of nearly whole time scale	Field mapping, plane table work, final report; 6 hours credit; opportunity for advanced work, tour from Louisiana to camp. Also course of short tours for graduate students in Gulf Coast area.
Macalester College, St. Paul, Minn.	.....	Occasionally; 6 weeks	.....	.....	.....	Vertebrate paleontology	Collection and preparation of material; 3–4 hours credit
Miami University, Oxford, Ohio	Eastern United States	Annually; 2 weeks, June 10 to late June	Men and women, 25–30; 1 instructor and assistants	$45	General geology, advanced students given preference	Structure, stratigraphy, geomorphology, economic geology	Tour, final report; 2 hours credit
	Western United States and Canada	Annually; 8 weeks, mid-June to early August	Men and women, 16; 1 instructor and assistants	$200	General geology, advanced students given preference	Structure, stratigraphy, geomorphology, economic geology	Tour, final report; 6 hours credit
Monmouth College, Monmouth, Ill.	Western United States	Annually (starting 1940); 6 weeks, June 15–August 1	Men	.....	.....	Rocky Mountain and Colorado Plateau geomorphology, glaciation, and stratigraphy	Tour, final report; 2–3 hours credit

TABLE 2—*Continued*

Institution	Locale	Time	Personnel	Cost	Prerequisites	Subjects Stressed	Nature of Work and Credit
Montana School of Mines, Butte, Mont.	Near Butte, Mont. (30–50 miles east); temporary camps	Annually; 3 weeks, early to late September	Men, women under special arrangement, 20–25; 3 instructors	$40	General geology, mineralogy, structure, petrology, surveying	Pre-Cambrian, Paleozoic, Mesozoic, and Tertiary stratigraphy and structure, economic geology	Field mapping, plane table work, final report; 3 hours credit; opportunity for advanced work
Nebraska, University of, Lincoln, Neb.	Western United States and Black Hills, S.D.; permanent camp in Black Hills	Annually; 6–7 weeks, early June to mid- or late July	Men, 12–24; 1–2 instructors	$67	General and historical geology, stratigraphy, mineralogy	Structure, stratigraphy, ore deposits, correlations	Tour of Western States, Black Hills field camp, field mapping, plane table work, final report; 6 hours credit; opportunity for advanced work
Nevada, University of, Mackay School of Mines, Reno, Nev.	Eastern Nevada; temporary camps	Annually; 10 weeks, May 15–July 25	Men, 8; 3 instructors	Outside students not accepted at present	Eight best upper-division students in geology and mining engineering at Nevada	Paleozoic stratigraphy and structure, mining geology	Field mapping, plane table work; 4 hours credit (S. Frank Hunt Geologic Foundation)
North Dakota, University of, Grand Forks, N.D.	Ontario, Canada	Occasionally; 5 days, late May to early June	Men, 8; 1 instructor	.....	Junior or senior majors in geology and mining engineering	Pre-Cambrian rocks and glaciation	Tour; no credit
Ohio University, Athens, Ohio	New England, Canada, Great Lakes region	Annually; 16–18 days, August 10–28	Men and women, 30; 1 instructor and assistant	$115; outside students not solicited	6 hours of geology and geography	General geography and geology	Tour, final report; 3 hours credit
Oklahoma, University of, Norman, Okla.	Arbuckle Mountains, Okla.; temporary camps	Annually; 5 weeks, June	Men, 15; 1½ instructors	$50	Elementary geology and surveying	Paleozoic stratigraphy and structure	Field mapping, plane table work, final report; 5 hours credit; opportunity for advanced work; permanent camp in Ardmore Basin planned
Pittsburgh, University of, Pittsburgh, Pa.	60 miles east of Pittsburgh; permanent buildings	Annually; 2 weeks of a 10 weeks' surveying course devoted to geology	Men, 25–50; 2 instructors	No outside students	General and historical geology, and mineralogy	Sedimentary rocks, stratigraphy, and structure	Field mapping, plane table work, final report; 2 hours credit
Redlands, University of, Redlands, Calif.	Southeastern California and Arizona	Annually; 5 days, late July	Men and women	.....	Physical geology	Geomorphology and petrology	Trip, field mapping, final report; 1 hour credit
Southern Methodist University, Dallas, Tex.	Trans-Pecos, Texas or tour of Southwest; temporary quarters	Usually annually; 3–6 weeks during summer	Men, 6–8; 1 instructor and assistants	$90	6 hours of geology	Folded and faulted sedimentary rocks, stratigraphy, paleontology	Field mapping, plane table work, final report; 3 hours credit for 3 weeks, 6 hours for 6 weeks; advanced work

TABLE 2—*Continued*

Institution	Locale	Time	Personnel	Cost	Prerequisites	Subjects Stressed	Nature of Work and Credit
Texas Christian University, Fort Worth, Tex.	Texas Big Bend area, Sierra Blanca to Langtry; temporary camps	1940 and alternate years; 6 weeks, early June to mid-July	Men and women, 12–16; 1 instructor and assistant	$100	Junior standing, at least 12 hours in geology	Paleozoic and Mesozoic structure and stratigraphy, geomorphology, igneous geology	Field mapping, plane table work, final report; 6 hours credit
Tulsa, University of, Tulsa, Okla.	Missouri, Oklahoma, Colorado; temporary quarters	Occasionally; 4 weeks, June 10–July 10	Men, 8; 1 instructor	No outside students	Physical and historical geology	General geology and field methods	Field mapping, plane tabl work; 4 hours credit
Vanderbilt University, Nashville, Tenn.	Western United States and back	Occasionally; 6–8 weeks, from mid-June	Men, 10–15; 1 instructor	$350	1 year of general geology	Various phases of geology	Tour, field mapping, final report; 4 year-hours credit
Yale University, New Haven, Conn.	May offer summer field course in 1940 but details not available at present						

DISCUSSION: GEOLOGY ALONG THE SOUTHERN MARGIN OF THE ABSAROKA RANGE, WYOMING

C. MAX BAUER
Yellowstone National Park

This contribution by John David Love[1] to the geology of the southern part of the Absaroka Range adds materially to our understanding of the stratigraphy and geological history of Yellowstone Park. Covering a scope of structure, stratigraphy, and geologic history it is of a type that is most needed to understand the complex history of the Middle Rockies.

The meat of this paper, however, might have been presented in a much shorter manner. There is much drawing upon the literature on other areas that does not add to the geology of the area mapped. In some cases it is doubtful if the conclusions reached are correct for the Middle Rockies. For example, to quote: "Upper Mesaverde and younger Cretaceous rocks are not present here, and time did not permit a study of them in the adjacent area three miles east of Red Creek." Yet the author proceeds to discuss "first pulses of the Laramide Revolution" by reference to the work of others from central Utah to Montana and the Dakotas. Hence the first three items listed in his summary are based on the testimony of others on other localities. Although these particular conclusions may be correct, they are illustrative of the lengthy paper which expands the blanket of its discoveries to cover a much larger region than the area studied. Even while so doing he states "the Laramide Revolution was not a movement affecting all mountain ranges simultaneously."[2] (This statement is not proven.) It would be better to confine his discussions to the contribution which his area makes to a better understanding of the Middle Rockies themselves.

A number of new formation names have been used for Eocene

[1] "Geology along the Southern Margin of the Absaroka Range, Wyoming," *Geol. Soc. Amer. Spec. Paper No. 20* (1939).

[2] *Ibid.*, p. 104.

and Oligocene strata which seem to be justified because of the difference in lithology and, to a certain extent, in fossil content, and because further work in the Absaroka Range may be promoted by using the terms suggested in this paper.

In reply to the author's statement that the close of the Laramide revolution must be arbitrarily chosen I would state that for central Wyoming and for the Middle Rocky Mountains the close of Laramide deformation can be clearly defined by an understanding of the character of forces effecting the deformation. Throughout the Eocene and into the early Oligocene the forces causing folding and faulting were compressional with relatively little uplifting of the region. The plant and animal fossils of the region indicate mild climate and low elevation throughout the Eocene epoch. Such changes as occurred in the area of the Absaroka Mountains may be well accounted for by the piling-up of volcanic debris to a thickness of 5,000–6,000 feet.

After the deposition of the Oligocene White River formation the forces causing deformation were largely epeirogenic or those of uplift and tension, in which normal faults predominate. It is true that there were later local folds and possibly some reverse faulting, but this deformation followed the normal faulting of the Miocene and is assigned to late Tertiary. Therefore, the Laramide revolution may well be closed with the Oligocene.

As stated before, I am convinced that a widespread plain of erosion and deposition was developed in central Wyoming in the late Eocene. Since in the basins it was a plain of aggradation, it may not be correct to call it a "peneplain." It is a subsummit plain of great extent in the Wind River Range and bevels the pre-Cambrian rocks at about 11,000 feet elevation in the central part and at about 10,500 feet in the southern part. It has been referred to by Blackwelder and others as the "Wind River Peneplain" and is here an erosional plain. To the east this plain is buried beneath White River deposits. Immediately to the north of the Wind River Range no comparable plain is now traceable because of volcanic disturbance. In the Absaroka Range, and in Yellowstone Park, volcanism which had the effect of uplift interrupted erosion cycles many times throughout the Tertiary.

This plain represented by the top of the late Eocene deposits and the base of Sweetwater member of the Oligocene in the Sweetwater escarpment is now at an elevation of 7,200–7,500 feet and is a very regular surface. Deformation has brought about the difference in elevation between the plain along the escarpment and the erosional plain in the Wind River Range. At the time this plain was formed it was much nearer sea-level than it is today and, because of its low gradient and distance to the sea, more nearly approached base level than any plain in the region developed since that time. Moreover, Eocene time was fully half that of the entire Tertiary, and therefore ample time had elapsed since the earlier deformations to develop this plain.

There was some uplift in early Oligocene time, but the Oligocene was essentially a period of violent volcanism and aggrading streams throughout the Middle Rockies and eastward on to the plains. The erosion supplementing this general activity was localized in the areas of especially rapidly growing mounds of pyroclastic material where torrential rains played a great part in supplying the means for spreading the material.

A former statement of mine that Wind River began on the early Oligocene surface is an error. However, it is quite certain that the northward course of the drainage was established by superposition before Miocene deformation had gone very far, and there is no evidence to indicate that Wind River is post-Miocene.

Post-Oligocene deformation (most probably early Miocene) brought about general uplift of all the area of the Middle Rockies. Two lines of evidence at least attest to this: first, the fossil flora and fauna indicate increased aridity; second, the beginning of general stream degradation. However, the Granite Range, which up to this time had been relatively high, lagged behind the general uplift to the extent of 2,500–3,500 feet, and thus the low-lying soft White River deposits in this neighborhood escaped erosion and are still preserved.

The southeastward course of the upper Wind River has no doubt been influenced by the relatively depressed block of the Granite Range, but the northward course of Wind and Big Horn rivers across the Owl Creek and Big Horn ranges must have been established before the relative depression of the Granite Range. Further-

more, the large bend to the east of this river in the vicinity of Riverton and also in the vicinity of Worland is due to the preponderance of sediment brought in from the northwest. This shifting toward the east where the stream crosses less-resistant material has continued through the late Tertiary and Quaternary epochs. A similar shifting or crowding of streams was pointed out by Mackin in the northern part of the Big Horn basin.

Contrary to Love's statement, both Big Horn basin and Wind River basin had been so filled with sediment by the close of the Eocene that only the higher peaks of the Wind River, Granite, Owl Creek, and Big Horn ranges protruded above the plain. It is true that some of the granite knobs rose 1,200–1,500 feet, but they presented no more obstacles to the principal streams than the Granite Range does to the Sweetwater River today. Since the Oligocene was a period of aggrading streams in this region, it is likely that by the close of the Oligocene even these peaks had been buried by sediments from the west. There is no accordance of altitude of the higher peaks of any of these ranges. On the contrary the most consistent plain of erosion is found 1,500 or more feet below their summits. Hence, it does not appear that any appreciable part of the late Oligocene plain was a plain of erosion on any of the older ranges but was due rather to a spreading of materials derived from eruptives of the Yellowstone Park region. Nearly nine-tenths of the material was deposited directly from volcanoes and much of it only partially re-worked by streams.

Love rejects the idea of a late Eocene plain by saying: "The Wind River surface could not have been formed prior to the close of Wiggins [Oligocene] time, [and] . . . . the plain could not have developed . . . . while at Split Rock [on Sweetwater River] Middle and Upper Miocene strata were being deposited."[3] Though earlier he states that "the formation [at Split Rock] has not been named or described, and its areal extent has never been mapped."[4] So it seems his evidence does not warrant the conclusions he makes.

The Miocene erosion surface which lies below the rhyolite series in Yellowstone Park had a greater relief than the present topography. Hence it is clear that benches and terraces formed after the Oligocene are not peneplains but pediments.

[3] P. 113. [4] P. 112.

REVIEWS

Recent Marine Sediments. Edited by PARKER D. TRASK. Tulsa: American Association of Petroleum Geologists, 1939. Pp. 736. $5.00.

This book is the latest of a group made possible by the revolving publication fund of the Association. The various articles were prepared under the direction of a subcommittee of the Committee on Sedimentation of the Division of Geology and Geography of the National Research Council. The nine members of this subcommittee consisting of Carl W. Correns, Stina Gripenberg, W. C. Krumbein, Ph. H. Kuenen, Otto Pratje,[1] Roger Revelle, F. P. Shepard, Henry C. Stetson, and Parker D. Trask contributed eleven of the thirty-four separate articles. Gripenberg and Krumbein each prepared two papers, and Revelle and Shepard are joint authors of a second paper. In addition to performing an excellent job of editing and developing a unity of form of the various papers, Trask prepared one article and translated one Swedish and seven German manuscripts. In the latter Trask was assisted by Marie Siegrist in four articles.

Other contributors who are not members of the subcommittee include Filip Hjulström, R. Dana Russell, H. W. Harvey, Richard Joel Russell, Walter Häntzschel, James H. C. Martens, E. M. Thorp, K. Lüders, C. H. Edelman, Kaarl Münster Strøm, W. Schott (2), C. E. ZoBell, W. P. Kelley, Ralph E. Grim, O. E. Radczewski, Jun-ichi Takahashi, E. Wayne Galliher, Hiliary B. Moore, W. H. Twenhofel, F. J. Pettijohn, Martin Mehmel, and Jack L. Hough.

The books contains 736 pages, of which 664 are in the text and the balance in author, citation, and subject indexes. Each individual paper has a good list of references making a total of 1,448, of which about 1,100 are not duplicated. It is interesting to note that the contributions of the Europeans and Americans usually contain many more references to articles published in their own continent, even though the subject has been studied on both continents. Two European articles containing a total of 123 references show only two of American publication. The other European contributors show a broader knowledge of American literature. The

[1] The paper by Otto Pratje on "Sediments of South Atlantic Ocean" was delayed because of a misunderstanding and could not be included in the book, but has been published in the *Bull. Amer. Assoc. Petr. Geol.*, Vol. XXIII (1939), pp. 1666–72.

American writers include, in most cases, a more cosmopolitan bibliography, though not always complete. Regardless of what inferences might be made, the workers in each group should gain by having these references called to their attention.

The majority of the pages are well illustrated by maps and diagrams, and much material is presented in chart or table form. In general the typography is excellent, characteristic of the Association publications, and there are few errors in proofreading. On page 736 four errata are listed and the reviewer noted only a few others, all of obvious correction.

Most of the papers were received by the editor during the last months of 1937 and the first half of 1938. Several are summaries by the specialists of his own work during a period of years and are in large part published in other papers or books; others show the advance of knowledge by numerous workers; and a few are new contributions published for the first time.

The several subjects are grouped in seven parts, i.e.: (1) "Transportation," (2) "Relation of Oceanography to Sedimentation," (3) "Deposits Associated with Strand Line," (4) "Near-Shore Sediments—Hemipelagic Deposits," (5) "Pelagic Deposits," (6) "Special Features of Sediments," and (7) "Methods of Study." Each part contains material that is important in the major study, but Parts 2, 3, 4, and 6 are especially valuable and suggestive of lines of much-needed additional research.

The article by Fleming and Revelle on the physical processes in the ocean is especially valuable. In this comprehensive discussion are many useful observations of ocean-water properties and currents which are of importance in understanding the conditioning of marine environments and their deposits. The utility of studies of this type as a means to more thorough interpretation of ancient marine deposits should not be overlooked.

As the major portion of the geologic column is composed of materials deposited in near-shore and shallow continental-shelf environments, the two groups of papers discussing deposits associated with the strand line and the hemipelagic areas should be of major interest to academic and petroleum geologists alike. Space does not permit an adequate review of the thirteen articles included in Parts 3 and 4, nor would it be fair to state that particular contributions are especially noteworthy as they are all well done and emphasize fundamental factors and conditions of important environments.

The Russells and Krumbein in their studies of Mississippi river and delta sediments demonstrate that a master-environment may produce a

unity of deposit but that the sediments do vary locally and may have a wide range of type depending on the varying conditions within the environment. It is necessary, therefore, to study and evaluate these variables for a large number of examples of the major environments, and Krumbein concludes that with such facts in hand a pattern can be developed that will be useful in the interpretation of ancient deposits.

Shepard reviews briefly some of the continental-shelf areas of the world and suggests from the nature of the sediments studied that the shelves or shoal-water platforms do not represent areas where deposition is occurring at the present time. He emphasizes the importance of shoreline accumulation and the by-passing of sedimentary materials to the slopes and depths beyond the escarpment at the outer margin of the shelf. He concludes, however, that during the past geologic periods the shelves may have been sites of large sediment accumulations.

The summary of sedimentary conditions on the east coast of the United States from Cape Cod to middle Florida by Stetson (derived largely from a longer paper published elsewhere) shows that bottom and tidal currents are effective sorting agencies in water up to 60 meters depth and that currents such as the Gulf Stream are responsible for sweeping the banks or shelf areas and causing deposition of sand in deep water while contemporaneous muds and silts may be accumulating in shallow-water sites. Important conclusions for the Atlantic Coast environment are that "grade size does not decrease uniformly in an off-shore direction," that "sedimentation along the margins of a major ocean must not be considered typical of an inland sea," and that "rivers are of practically no importance in supplying sediment to the shelf at present."

Revelle and Shepard present new data with a general summarization of previous publications of work done along the California coast. There is considerable difference in the conditions along the Atlantic and Pacific coasts. The nature of the submarine topography, the amount, character, and distribution of debris supplied by the streams, and the nature of the ocean currents all tend to make this a highly specialized but interesting study.

The reviews of findings in the Baltic and North seas in separate papers by Gripenberg, Lüders, and Edelman, and of the black mud deposits by Strøm, are excellent progress reports that indicate the need for more extensive work and demonstrate that highly specialized conditions may produce a wide variety of contemporaneous sedimentation in closely adjacent localities. As Strøm concludes, the relation between "ventilated" and "unventilated" deposits in the same basin of deposition may explain some

of the limestone and black-shale sequences of the geologic column and also have an important bearing on the preservation of organic material which is the source of mineral oil.

Part 6, "Special Features of Sediments," contains several articles of especial interest to petroleum geologists. ZoBell discusses the work of bacteria in sediments and reviews some of the opinions of the relation of bacteria in the generation of petroleum. Trask gives a good review of the present knowledge of the quantity, nature, source, and distribution of organic material in recent marine sediments and a brief discussion of some of the environments of accumulation. The review of the properties of clay by Grim is thorough, and the complete bibliography will be very useful to other workers. The glauconite problem is summarized by Takahashi and Galliher, and faecal pellets are described by Moore.

In Part 7 the discussion of bottom-sampling apparatus by Hough is valuable for workers who need a handy and concise general review of such equipment. It is apparent that apparatus for sampling certain types of sediments is very successful but that each has its limitations. Ingenuity has a free rein to devise better samplers to meet broader requirements.

The fifty-eight pages used for the articles on "Graphic Presentation and Statistical Analysis of Sedimentary Data" and "Mineral Analysis of Sediments" might have been used to better advantage as these subjects appear in a form very similar to a recent publication by the same authors, and little if any new material has been presented. Trask states in his preface that there are many pressing problems in marine sedimentation, and the reviewer believes that some discussion of the status of such problems and methods of study and the outlining of projects would have been desirable. Very useful would be chapters on the geomorphology of marine shorelines and the relation to marine deposits, on the matter of contemporaneous deformation of marine sediments, and on the primary structures of recent sediments, such as ripple, wave, and current marks, stratification, compaction, and many other features. To constitute a true symposium there should be included a careful outline of plans for future work with an attempt made to co-ordinate the lines of attack and sites of operation.

There can be little doubt of the pertinency of the investigation of contemporaneous sedimentation. Not only have the specialists of sediments oriented their investigations to this path as an essential accessory before the fact, but the petroleum industry needs established results of observation and research to further its development. With the need to explore and search for petroleum traps in lenticular sands, formations of variable

porosity and permeability, or accumulations and segregations in materials of a wide range of lithology, the doctrine that the present is a key to the past cannot be overemphasized. The question of where and what is the source of the oil of each developed field has given the petroleum geologists many a restless night before the discovery well, and the time is here when concrete ideas on the subject are necessary before embarking on a costly program of geophysical and drilling exploration. The reviewer knows of no better approach to fundamental knowledge than by the complete analysis of recent sediments and a careful piecing of these clues step by step through progressively older rocks that have suffered the vicissitudes of age and alteration by the various agencies operating in the zone of penetration of the lithosphere.

A. C. TESTER

Stratigraphy and Paleontology of the Lower Mississippian of Missouri, Part II. By VARIOUS AUTHORS. ("University of Missouri Studies," Vol. XIII [1938]). Pp. 242; pls. 28.

Several papers dealing with the stratigraphy and paleontology of the Lower Mississippian horizons in Missouri are combined in a single publication. These are:

1. "Stratigraphy and Paleontology of the Northview and Hannibal," by E. B. Branson.

2. "Blastoidea from the Chouteau of Missouri," by Raymond E. Beck.

3. "Crinoidea from the Chouteau of Missouri," by Raymond E. Beck and I. A. Keyte.

4. "Pisces from the Lower Mississippian of Missouri," by E. B. Branson and M. G. Mehl.

5. "Conodonts from the Lower Mississippian of Missouri," by E. B. Branson and M. G. Mehl.

6. "Lower Mississippian Nautiloid Cephalopods of Missouri," by A. K. Miller and W. M. Furnish.

7. "Summary of Lower Mississippian Stratigraphy," by E. B. Branson.

Taken together, these papers comprise a comprehensive treatise of the Lower Mississippian of this region. In addition to complete descriptions of the fauna, the volume also contains numerous plates which are unusually well executed.

RAYMOND E. JANSSEN

"Limestones of West Virginia." By JOHN B. MCCUE, JOHN B. LUCKE, and HERBERT P. WOODWARD. *West Virginia Geological Survey*, Vol. XII. Morgantown, W.Va., 1939. Pp. 560; pls. 38; figs. 15; 1 map.

"Greenbrier County." By PAUL H. PRICE and E. T. HECK. *West Virginia Geological Survey*. Wheeling, W.Va., 1939. Pp. 870; pls. 53; figs. 23; 2 maps. $3.00.

The report on the limestones of West Virginia is intended primarily as an economic report, and as a consequence other geological phases, such as stratigraphy and paleontology, are given little space. Information is given regarding location, quantity, and quality of the many different limestone deposits, as well as statistical, technological, and economic data on the limestone industry. A map of the state is included which shows the outcrop of limestones and the locations from which all samples were taken for study.

The volume on Greenbrier County is a general geologic and economic report with a chapter on the historical and industrial development; one on physiography; seven on geologic history, structure, and stratigraphy; four on mineral resources; and one on paleontology. There is also an Appendix giving all available spirit-level bench marks and railroad levels for the county. The book is accompanied by an atlas containing a topographic map and a multicolored geologic map with structure contours on the Sewell coal, both to the scale of 1:62,500.

These reports are carefully done in great detail and represent important contributions to the study of the geology of the Appalachian region.

LOUISE BARTON FREEMAN

"On the Geology and Tectonics of the Outokumpu Ore Field and Region," by HEIKKI VÄYRYNEN. (*Bulletin Commission géologique de Finlande, No. 124.*) Helsinki, 1939. Pp. 91; figs. 11; maps 2.

"Comptes rendus de la Société géologique de Finlande." (*Bulletin Commission geologique de Finlande, No. 125.*) Helsinki, 1939. Pp. 119, figs. 45; pl. 1.

These bulletins of the Geological Commission of Finland are a continuation of the excellent work being done by that organization. The papers are well written and illustrated, some being published in English and others in German.

Bulletin 124 covers the geology and tectonics of the Outokumpu ore

district and the author states that a detailed report covering the petrography of the area is being prepared. The Outokumpu ore was discovered by means of systematic prospecting in 1910, but it was only after the Finnish state had become sole owner of the mine in 1924 that mining was extended and a concentrating plant erected. This copper ore forms a sheetlike mass following the bedding planes of the enclosing quartzite. On the basis of his study Väyrynen concludes that the ore deposition took place while the thrust movements of the Outokumpu nappe were coming to a close and before the intrusion of the granite; that is to say, while the rocks now at the surface were so deep that the dehydration of the serpentines and formation of the calc-silicate rocks had attained considerable proportions.

Bulletin 125 contains seven papers, among which might be mentioned especially another valuable report by Matti Sauramo on his Quaternary studies in Finland. This treats of the mode of land upheaval in Fennoscandia during late Quaternary time.

Included also is a contribution by E. H. Kranck, entitled "The Rock-Ground of the Coast of Labrador and the Connection between the Pre-Cambrian of Greenland and North America," in which he points out the close relation between the problems of pre-Cambrian geology in Labrador and Greenland and those of Fennoscandia.

LOUISE BARTON FREEMAN

"On a Second Collection of Fossils and Rocks from Kenya Made by Miss M. McKinnon Wood." *Monographs of the Geological Department of the Hunterian Museum, Glasgow University*, Vol. V. ("Glasgow University Publications," Vol. XLIX.) Glasgow: Jackson, Son & Co., 1938. Pp. 116; figs. 10; pls. 11.

Included in a single volume are nine papers by various authors concerning the rocks and fossils of Kenya. This constitutes a sequel to Monograph IV, issued in 1930. Together, these publications describe the specimens contained in the M. McKinnon Wood collections in the Hunterian Museum of Glasgow University. Papers included in the present monograph are:

1. "Some Further Geological Observations on the Coastlands of Kenya," by M. McKinnon Wood.

2. "*Palaeanodonta* from Kenya and Burma," by J. Weir.

3. "The Jurassic Faunas of Kenya with Descriptions of some Brachiopoda and Mollusca," by J. Weir.

4. "Additions to the Neogene Molluscan Faunas of Kenya," by J. Weir.

5. "Neogene Echinoidea in the Second McKinnon Wood Collection," by Ethel D. Currie.

6. "A Second Collection of Fossil Corals from the Kenya Coastlands Made by Miss McKinnon Wood."

7. "On Some East African Neogene Foraminifera," by C. D. Overy.

8. "Report on the Fossil Plants in Miss McKinnon Wood's Second Collection from Kenya," by S. Williams.

9. "Igneous Rocks from the Neighbourhood of Mount Jombo and the Sabaki River," by G. W. Tyrrell and Agnes T. Neilson.

RAYMOND E. JANSSEN

"Highway Geology, Philadelphia to Pittsburgh," by BRADFORD WILLARD. (*Pennsylvania Geological Survey Bulletin, G 12.*) 4th ser. Harrisburg, Pa., 1939. Pp. 42; pls. 17.

"Guide to the Geology from Dauphin to Sunbury," by BRADFORD WILLARD. (*Pennsylvania Geological Survey Bulletin, G 13.*) 4th ser. Harrisburg, Pa., 1939. Pp. 25; pls. 7.

"Guide to the Geology of the Upper Schuylkill Valley." By BRADFORD WILLARD. (*Pennsylvania Geological Survey Bulletin, G 14.*) 4th ser. Harrisburg, Pa., 1939. Pp. 23; figs. 8; pl. 1.

"Guidebook to the Geology near Reading, Pennsylvania," by BRADFORD WILLARD and DONALD M. FRASER. (*Pennsylvania Geological Survey Bulletin, G 15.*) 4th ser. Harrisburg, Pa., 1939. Pp. 27; figs. 11.

Some of these guidebooks, published by the Pennsylvania Topographic and Geologic Survey, are based upon the annual trips of the Field Conference of Pennsylvania Geologists; others are derived from a series of educational field trips in geology sponsored by the Survey since 1935. In each book there is a discussion of the local geology, followed by detailed itineraries whereby a concept of the local rock formations may be formed or visits made to points of outstanding geologic interest in that particular area.

Bulletin, G 12, gives the geology of a section across the state from Philadelphia on the contact of the Coastal Plains deposits with the Piedmont crystalline rocks, across the valleys and ridges of the Appalachians and the bituminous coal region, to Pittsburgh on the west. The other three bulletins are concerned with more restricted areas.

The books are very well written and illustrated, fulfilling the requirements of the person with little technical training as well as giving a background to the geologist preliminary to more detailed studies.

LOUISE BARTON FREEMAN

"Petrography and Correlation of Deep-Well Sections in West Virginia and Adjacent States." By JAMES H. C. MARTENS. (*West Virginia Geological Survey*, Vol. XI.) Morgantown, W.Va., 1939. Pp. 255; figs. 8; pls. 22.

This volume is a result of the detailed study of drill cuttings from deep wells in West Virginia and adjacent states. Based on the examination of these cuttings, Mr. Martens has prepared accurate sections of rocks penetrated by several deep wells so distributed over the part of the state having known or possible oil and gas resources as to give as much information as possible about the characteristics of the underlying formations and their variations. Special attention was given to the sections of the Oriskany sandstone and the formations immediately above and below it.

The problem was approached by a consideration of the mineralogy of the samples, and in the case of the sandstones and a few other rocks heavy-mineral separates were made and examined. The author concluded that, since the heavy detrital minerals were limited to rather common ones, a very exact correlation between well sections and outcrops could not be made using this criterion alone. However, his observations agreed with earlier conclusions that the Oriskany was derived from an older sandstone rather than directly from igneous or metamorphic rocks.

A short section of the book is occupied with the mineralogy of sedimentary rocks in West Virginia, the classification of the minerals as to origin, and the occurrence and properties of individual minerals. In another section are given generalized descriptions of subsurface formations. The largest part of the book, 175 pages, is made up of detailed sample studies of sixty-nine wells, in each of which the various formations have been identified. Three generalized and three detailed sections are given, as well as a table of thicknesses of formations in thirty-three of the wells from which samples were examined. The photographic plates of thin sections and heavy mineral suites are very good.

LOUISE BARTON FREEMAN